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# SkyPort: payload: medical cooler for the skyport UAV

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UNDER MY SUPERVISION BY

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ENTITLED

# SKYPORT: PAYLOAD
# MEDICAL COOLER FOR THE SKYPORT UAV

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By

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**SENIOR DESIGN PROJECT REPORT**

Submitted to
the Department of Mechanical Engineering

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ABSTRACT

Access to basic healthcare is a major persisting problem around the globe, especially in rural parts of the world. One of the many facets of this problem is access to vaccine treatment. The transportation and storage of vaccines at the proper temperature is an issue that is still being solved and improved upon today. One of the common solutions to this problem is the use of passive coolers such as ice packs and other refrigerants. The potential issue with passive cooling is that the temperature cannot be actively controlled. This is evident, as many vaccines are wasted due to incorrect storage temperature. Additionally, these products are generally bulky in size. In order to solve both the issue of transportation and storage, we designed an active cooling system using thermoelectric modules that keep vaccines and blood samples at the proper storage temperature range of 2-8 °C. This device was designed to be transported by an unmanned aerial vehicle (UAV), and is equipped with a temperature control system as well as a battery pack. This delivery system was conceptualized and fabricated by the SkyPort social enterprise project, a group of mechanical engineers split into teams to focus on different aspects of the system. As the team responsible for the payload, we developed a device that stores up to 6 vaccine vials and 3 blood sample vacutainers at a temperature of 5 °C. The payload operates with a feedforward loop, controlled by the temperature of the chamber and environment. Our design operates in ambient temperatures of 40 °C for over 10 hours. The SkyPort UAV is a viable and innovative alternative to vaccine delivery because it does not rely on ground transportation infrastructure. In addition, the temperature control system maintains the vaccines and blood samples at the required temperature range, ensuring that they remain safe during transport. This is still a proof-of-concept design and can be improved upon further to produce a refined product. The device can be improved in terms of efficiency and manufacturability in addition to user interface.

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## Chapter 1 – Introduction

### *1.1 Problem Statement and Motivation*

Despite the growing advances in medical and transportation technologies, global healthcare faces many shortcomings. Each year, over 7.5 million children under the age of 5 die from malnutrition and mostly preventable diseases. The World Health Organization (WHO) reported that 6.7 million people died of infectious diseases in 2008 [1]. Although progress is being made towards identifying disease cases, the rate of accessible treatment still remains low according to the 6th Millennium Development Goal [2].

One of the targets of the 6th Millennium Development Goal is to achieve universal access to treatment for major diseases. In underdeveloped countries, ground transportation to isolated communities is extremely difficult due to poor infrastructure. In general, this issue causes delays and poor supply information. Poor supply information yields inventory overcompensation, which leads to wasted materials. From a medical perspective, supply information is essential due to the cost of vaccines and the priceless value of the human life.

In addition to poor transportation methods, vaccine waste due to incorrect storage temperature is a significant problem. In 2007, 151 million vaccine doses were wasted in developing countries due to improper refrigeration [3]. The WHO states that vaccines and blood samples must be maintained at a temperature range of 2-8 °C, although some less-common vaccines require different storage temperatures.

### *1.2 Project Objectives*

SkyPort is a social enterprise project founded by Micah Klaeser. The SkyPort project offers a solution, utilizing aerial transportation to deliver medical supplies. The

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[1] Shah, Anup. "Health Issues." *Global Issues: Social, Political, Economic and Environmental Issues That Affect Us All*. N.p., 27 Sept. 2014. Web. 18 Nov. 2014. http://www.globalissues.org/issue/587/health-issues.

[2] "MDG 6: Combat HIV/AIDS, Malaria and Other Diseases." *WHO*. N.p., n.d. Web. 15 Nov. 2014. http://www.who.int/topics/millennium_development_goals/diseases/en/.

[3] Hayford, Kyla, Lois Privor-Dumm, and Orin Levine. "Improving Access to Essential Medicines Through Public-Private Partnerships." *International Vaccine Access Center* (2011): n. pag. Web. http://www.jhsph.edu/research/centers-and-institutes/ivac/resources/IVAC-Improving-Access-to-Essential-Medicines.pdf.

SkyPort unmanned aerial vehicle (UAV) is a hybrid plane-quadcopter that combines both gliding flight with vertical takeoff and landing (VTOL). This configuration allows for a solution that is completely independent of road infrastructure. The SkyPort UAV is a fast and reliable alternative to ground transportation, and it encompasses the idea of just-in-time delivery, in which goods are received and delivered only when needed. This increases efficiency and decreases waste.

SkyPort is divided into three teams consisting of mechanical engineers: Airframe, Controls, and Payload. The Airframe and Controls teams are responsible for the design and fabrication of the SkyPort UAV, and the Payload team is responsible for the design and fabrication of the medical cooler. As the Payload team, we have developed a medical cooler to transport both vaccines and blood samples from medical facilities to undeveloped areas in sub-Saharan Africa. The addition of blood sample transport doubles the functionality of the SkyPort UAV, allowing it to facilitate medical research in addition to treating patients.

The most crucial aspect our team was responsible for involved maintaining the correct internal temperature of the medical cooler. Our goal was to create a well-insulated cooler that keeps vaccines and blood samples safe for an estimated maximum time of 10 hours. In order to ensure this safety measure, we created a temperature control system utilizing an Arduino microprocessor and temperature sensors. An insulated shell and active cooling with a thermoelectric module (TEM) maintains the internal temperature of the payload within the acceptable temperature range of 2-8 °C. Along with this requirement, we optimized the payload to have a low weight and volume since it is delivered with an UAV. Our final product is effectively balanced in terms of cooling efficiency, low weight, and small size.

In addition to producing a successful product, our team has developed positive relationships with the other SkyPort teams by communicating effectively to be successful as a whole. The teams depended heavily on each other in order to be consistent and successful. By the end of fall quarter, our team produced a mock-up of the highest rated design concept and organized a list of parts to be implemented in each subsystem. In the winter quarter, our team fabricated a prototype to run off of DC power. This allowed for the testing and optimization of the Heat Removal Subsystem components, whose properties influence the design of the Power Supply and Temperature Control subsystems. We communicated with the other SkyPort teams to validate and confirm our design decisions. By the end of winter quarter, we designed and implemented the remaining systems to produce a fully functional payload so that the remaining time could be spent improving the device's thermal efficiency and user interface.

Adding to the research and technology of a vaccine cooler not only contributes to SkyPort's goals, it encourages others to take advantage of aerial vaccine transportation on a global scale. We are also raising awareness of this issue so that others may expand and improve this technology, allowing for greater travel distances and storage capacity.

### *1.3 Literature Reviews*

Our design approach has changed in many ways since the start of our research. At first, we were guided by our advisor to use TEMs as part of our cooling system. We found that TEMs consist of two ceramic plates with semiconductor material in between. When a voltage is applied to the TEM, heat is transferred from one plate to another. One of the problems with the TEM is controlling the amount of current supplied to achieve the desired temperature, especially for vaccines. Another potential problem with TEMs occur when they are switched off. The heat stored at the hot end of the TEM goes back into the cooling system through the thermal bridge, resulting in heating. In the article "Computational Study on Temperature Control Systems for Thermoelectric Refrigerators," we read about an approach where the TEM is not switched off, but is supplied with a minimum voltage in order to improve its coefficient of performance significantly. Another way to improve the performance of the TEM is by adding a heat sink and fan to the cool side or hot side [4]. This has the potential to improve the efficiency of the device because it improves the heat dissipation from the hot side.

After consulting Dr. Hight, one of our team advisors, we came up with additional ideas for keeping the vaccines cool. One idea utilizes a phase changing liquid and good insulation, a method known as passive cooling. Using an insulation material such as

[4] Astrain, D., A. Martínez, J. Gorraiz, A. Rodríguez, and G. Pérez. "Computational Study on Temperature Control Systems for Thermoelectric Refrigerators." Journal of Electronic Materials 41.6 (2012): 1081-090. Web. 17 Nov. 2014.

Styrofoam, the temperature of the vaccines can be maintained at the correct temperature while conserving weight. This idea would be of good benefit to our project since it does not require a source of power for the cooling system, unlike TEMs. As a result, there could be a reduction in weight and overall complexity of the system. Overall, it could allow for an increased number of vaccines compared to using TEMs. However, this was not a viable option because the safety of vaccines and blood samples could not be regulated.

## Chapter 2 – System Level Design

### *2.1 Customer Needs*

Our project has one main potential user, but we believe that it can be adapted to fit the needs of additional customers and services. The main customers for this project are rural villages in Zambia, where SkyPort founder Micah Klaeser spent the summer conducting research. The transportation of goods via UAV is fairly new technology, but the applications are becoming more relevant and available. In addition to the main purpose of our project, the technology and design process could be used to make general advances in this service. Companies such as Deutsche Post DHL and Amazon have begun to develop and test UAVs for their delivery systems [5].

In order to optimize the final product, we needed to know as much as we could about the customer we are serving. The product specifications had to be justified by hard facts and optimized based on the customer need importance. Customer needs were refined by utilizing a process outlined in Chapter 5 of *Product Design and Development* [6]. The process of identifying the customer needs include five steps: gather raw data from customers, interpret the raw data in terms of customer needs, organize the needs into a hierarchy, establish the relative importance of the needs, and reflect on the results and the processes. Since our primary customer is based in Africa, it was extremely difficult to establish their needs. However, we used some ballpark information as a starting point.

Based on Klaeser's experience in Zambia, there are a few assumptions that we used to determine parameters for the payload design. Because they are mostly assumptions, they are analyzed with a factor of safety in consideration. These specification assumptions are based on a combination of Klaeser's information, vaccine requirements from the World Health Organization, and design parameters from the other SkyPort teams. In order to make use of these assumed customer needs, they were organized into a hierarchal table based on their priority. As shown in the table in

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[5] "DHL Parcelcopter Launches Initial Operations for Research Purposes." *DHL*. N.p., 24 Sept. 2014. Web. 17 Nov. 2014. http://www.dhl.com/en/press/releases/releases_2014/group/dhl_parcelcopter_launches_initial_operations_for_research_purposes.html.

[6] Ulrich, Karl T., and Steven D. Eppinger. Product Design and Development. New York: McGraw-Hill, 2012. Print.

*Appendix A.1*, the most important customer needs are as follows: the payload maintains allowable temperature for vaccines, the payload weighs less than 3 kg, the payload has a height and width under 90x90 mm, and the payload is insulated to maintain cooling for up to 10 hours. The customer needs that fall below the list stated above are as follows: the payload is fully enclosed within UAV fuselage during flight, the payload stores at least 12 vaccines, and the payload releases on command upon arrival. Since these customer needs were based on the other teams' specifications, some were changed during the course of this project. Due to unforeseen design constraints, our team altered the deliverables to an appropriate extent.

### *2.2 System Sketch*

In order to ensure our product serves its purpose, we have looked at who our potential users might be. A potential user will be a person who is licensed to administer vaccines. This might be a doctor, nurse, or pharmacist. One of our tasks is to make sure our product is relatively easy for a healthcare worker to use. Therefore, we designed a mechanism that does not require human interaction to detach from the UAV. Additionally, the payload itself is designed to account for user-friendliness. This involves an opening mechanism for direct access to the vaccines that is easily identifiable.

Before the payload is attached to the UAV, the person administering the vaccines will need to load the vials, syringes, and vacutainers. Our payload needs to be activated at least forty minutes before the vials/syringes are loaded, since this is the time required to achieve the storage temperature. Once the vials/syringes are loaded, the payload is attached to the UAV by using electromagnets that are mounted on to the UAV. Once the payload reaches its final destination, it is detached by turning off the electromagnets. We designed the payload to be as efficient as possible by making sure the vials/syringes can be taken out as quickly as possible with the least amount of heat entering the system. This takes into consideration the configuration of parts and the steps necessary to remove the vials from the payload. A design sketch is provided in *Appendix A.2*.

## *2.3 Functional Analysis*

The main function of our payload is to keep the inside at temperatures between 2-8 °C for about 10 hours. In order to achieve this, we used active cooling with TEMs and good insulation. TEMs require a heat dissipation system. We used a heat pipe as a means of removing the heat from the inside of the payload through the TEM. This system also requires a heat sink and fan in order to continue the heat dissipation. The inside of the payload is an aluminum block with slots for vials and vacutainers. Since aluminum has high thermal conductivity, it is beneficial for inducing uniform cooling on the inside of the payload. Furthermore, expanded polystyrene (EPS) foam is used as the insulation material. EPS foam has low thermal conductivity, low density, and is relatively cheap.

There are several constraints that are placed on our payload. Since we are mounting our payload to a UAV, we needed it to be light and small. The weight benchmark as set by the Airframe team is a maximum of 3 kg. The cross-section is a maximum of 90x90 mm, which is deemed reasonable but also flexible. In order to achieve these constraints, we determined the dimensions and weight of each component that is needed for our payload, having an overall width of 145.4 mm, a height of 114.8 mm, and a length of 338.3 mm. In order to use active cooling, we needed an energy source for our TEMs. Since batteries carry a significant amount of weight compared to the other components, the efficiency of the thermal system is important in order to keep the weight low.

## *2.4 Benchmarking Results*

Although the concept of a vaccine cooler is not the first of its kind, its application in our project is unique and innovative. We found that there are similar products in the market such as the Arktek™, Cool Cube™ 50 (VT-50), and the DHL drone. The Arktek™, which keeps vaccines cool for more than 30 days, was created by Global Good, a collaboration between Bill Gates and Intellectual Ventures. Global Good incorporated “various sensors to track how long the container is open and logged the temperature of the vaccines" every 15 minutes to ensure the safety of the vaccines [7]. This passive cooling product keeps vaccines safe for long periods of time, but it is large and requires road access to deliver. The product also costs $1100, which can be expensive for underdeveloped areas.

Another existing product is the VT-50 by VeriCor Medical Systems. They have developed different sized passive coolers that allow the vaccines to be kept safe for over 60 hours. They also have "insulated walls with cool cubes that are placed inside the overall cube" to provide cooling for longer periods of time [8].


***(a)*** ***(b)***

Sources: http://www.intellectualventures.com/assets_blog/Arktek_Blog.png

http://www.vericormed.com/wp-content/uploads/2014/01/Vericor-Cool-Cube1-300x210.png

***Figure 1:*** Arktek™ (a) and VT-50 (b) passive cooling vaccine storage devices.

A 6-in. cube volume has the capacity to hold 50 vaccines and weighs 5.44 kg (12 pounds). Just like the Arktek™, the VT-50 has a high capacity for vaccines and a long cooling duration. However, these products are not appropriate for use with a drone because of their high weight and large size.

[7] "This Bill Gates-Backed Super-Thermos Saves Lives With Cold Vaccines." *Co.Exist*. N.p., n.d. Web. 17 Nov. 2014. http://www.fastcoexist.com/1682578/this-bill-gates-backed-super-thermos-saves-lives-with-cold-vaccines.

[8] "Cool Cube™ 50 (VT-50) - Vaccine Transport Cooler - VeriCor Medical Systems." *VeriCor Medical Systems*. N.p., n.d. Web. 17 Nov. 2014. http://www.vericormed.com/product/vaccine-cooler-cool-cube-50-vt-50/.

Both the Arktek™ and VT-50 would be ideal for our project if they met the weight and size requirement to be used in a drone. Another product that is important to consider is the DHL drone delivery system, shown below in *Figure 2*.

Source: https://www.flickr.com/photos/samchurchill/14586999783

***Figure 2:*** DHL parcelcopter drone.

DHL is conducting "trials on a German island where they deliver medicine using their drone and parcel payload" [9]. They do not have specifications about their device publicly available other than its weight of 1.2 kg. All of these products address the same customer: people who need vaccines but do not have access to power. The DHL drone also needs a way to track the safety of the vaccines. Our project addresses the needs that the other products cannot.

*2.5 System Level Issues*

The three main design parameters involved in our project are heat transfer efficiency, volume, and weight. The heat transfer efficiency is partly dependent on the volume. As a result of preliminary research and brainstorming, our team developed a set of designs that incorporate TEMs as the source of cooling. These designs vary in terms of the aforementioned parameters as well as other design considerations such as machinability and power consumption. Each of the design options assume 12 vials will be transported, and they vary in shape and size. Each design also incorporates a heat pipe and external fan to direct the flow of heat from the payload interior to the TEM mounted

[9] Ibid.

outside. One of the designs utilizes a heat pipe that is located above the vials. This differs from a design where the heat pipe is located between the vials because it allows the payload to be slightly thinner. This improves the machinability and lowers the weight and volume, but also compromises the heat transfer efficiency. Without data from tests or mockups, our team could not accurately rate these designs. Based on our intuition and brainstorming, our team developed selection matrices that gave us a better understanding of what to prioritize in our design considerations. These matrices are provided in *Appendix A.4*. After consulting with our advisors, a design concept was settled upon. This design utilizes a heat pipe that is located between two rows of slots. The top row is designed for vaccine vials and the bottom row for vacutainers.

### *2.6 System Level Design Layout*

The main subsystems that our design project is comprised of are as follows: Heat Removal, Outer Insulation, Temperature Control, and Power Supply. These subsystems serve as a breakdown of components with similar functions in close proximity to each other. Components in the Heat Removal Subsystem include a TEM, planar heat pipe, heat sink, fan, and the aluminum inner chamber. The Outer Insulation Subsystem consists primarily of EPS foam and birch plywood panels. The Temperature Control Subsystem consists of an Arduino microcontroller, buck converters, relays, and temperature sensors in a 3D printed enclosure. The Power Supply Subsystem consists of several lithium-ion battery cells, also housed in a 3D printed enclosure.

Since there is a high percentage of wasted vaccines due to incorrect storage temperatures with passive cooling systems [10], our team decided to use active cooling. By using active cooling we can precisely control the temperature of the inner chamber. There are several active cooling systems that can be used to keep the vaccines cool at their acceptable temperature. Two of these devices are the TEM and the compressor-based system. For our active cooling device we decided to use a TEM that pumps heat out from the inner chamber to the environment. Since TEMs are traditionally known to be inefficient, we needed a good heat dissipation system and a highly resistive insulator. The TEM was chosen over the compressor based system refrigerator for several

[10] Ibid.

reasons. Since space and weight is a critical constraint, a TEM is a solution because it is relatively smaller and lighter than a comparable mechanical system. Unlike a mechanical refrigeration system, the TEM works without any moving parts so they are virtually maintenance free. Also, compressor based systems cannot be fabricated without using chlorofluorocarbons or other chemicals that may be harmful to the environment, unlike the TEM that does not use or generate gases of any kind. As mechanical systems decrease in size, their efficiency lowers. Implementing a compressor based system refrigerator into our design would not be practical.

The vaccines are placed inside an aluminum enclosure to keep the vaccines in place. Due to the high thermal conductivity of aluminum, heat is removed from the vaccines to the TEM at a faster rate. In order to ensure good contact between the aluminum and the heat pipe, thermal interface material is used. This material improves the thermal conductivity between the aluminum as long as the pieces of aluminum are securely fastened. The EPS foam is the main insulator because it is lightweight, impact resistant, and has low thermal conductivity. A heat pipe connects the inner chamber with the TEM. The insulation and heat dissipation components require additional space to be effective, so we utilized a planar heat pipe to prevent the components from interfering. The TEM pulls heat from the inner chamber through the heat pipe, and this heat is then dissipated into the environment with the fan and heat sink. The basic operating principle of the payload design is shown below in *Figure 3*.

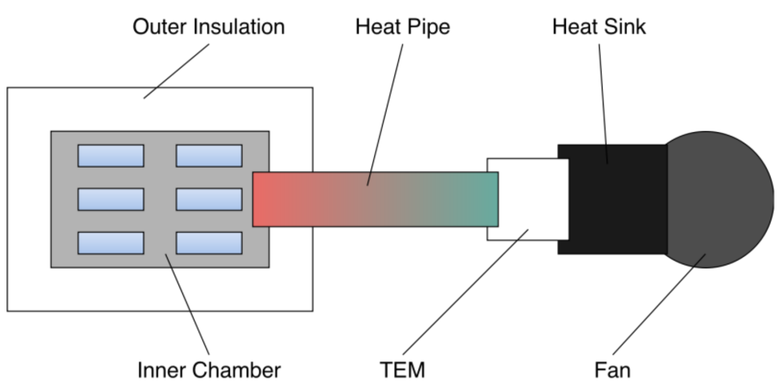



***Figure 3:*** Basic schematic detailing the flow of heat from left to right.

### *2.7 Team and Project Management*

When we embarked on this senior design project, it was difficult to organize our schedules and abilities in order to be effective. It was difficult to find meeting times for our group to work together due to our varied schedules. This forced us to be more productive during the few times we were able to meet. Our design requires heat transfer analysis, and the utilization of a temperature control system. Both of these concepts are very technical and were challenging to accomplish. Initially, calculations were incorrect several times, but with the aid of our advisor and graduate students we were able to complete simple heat transfer analysis to simulate our design. Our lack of knowledge delayed our goals because we could not make any decisions without having some calculated results. Once we were able to work together to achieve some results, we were able to look into the components of the payload.

In order to successfully complete our project, we acquired funding from the Santa Clara University's School of Engineering as well as the Roelandts Grant. The funds from these beneficiaries amounts to $3100, which was enough to account for the parts, materials, and services required for our project. The initial estimated budget for supplies amounted to $1600 and accounted for multiple prototypes. To account for possible setbacks, we secured almost twice this amount in the form of the grants mentioned above. The total amount spent towards the project was $3042. See *Section 8* and *Appendix B.1* for a detailed budget.

## Chapter 3 – Heat Removal Subsystem

### *3.1 Thermoelectric Module*

Due to the potential dangers of passive cooling systems as discussed in *Section 2*, the SkyPort medical cooler utilizes a thermoelectric module (TEM). This active cooling device operates on the principle known as the Peltier effect, in which a temperature gradient is created between each side, induced by an applied electrical current. A characteristic of TEMs is that the temperature is proportional to current. As shown in *Figure 4*, TEMs consist of two ceramic plates with alternating semiconductor material in between. The plates serve as thermally conductive junctions, known commonly as the "hot side" and "cold side". The flow of electrons through the TEM also permits the flow of heat, in a process known as joule heating. Joule heating is generated when there is electrical current flow through the semiconductor material. At the microscopic scale, the heat generated results from the rise in vibrational energy of ions that causes the rise in temperature of the semiconductor [11]. This creates a temperature difference in which heat is absorbed through the "cold side" and rejected out of the "hot side". The following diagram shows the basic operating principle.

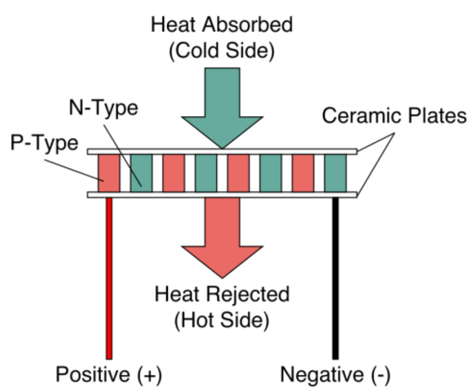



***Figure 4:*** Operating principle of a thermoelectric module.

Compared to other active cooling systems, such as vapor-compression systems normally found in refrigerators, TEMs are not especially efficient in terms of the coefficient of performance (COP). This represents the ratio of heat removed to the

[11] Vián, J.g, D. Astrain, and M. Domínguez. "Numerical Modelling and a Design of a Thermoelectric Dehumidifier." Applied Thermal Engineering 22.4 (2002): 407-22. Web.

required work. For a typical consumer refrigerator, the COP can be expressed in terms of $T_H$, the surrounding temperature, and $T_C$, the internal temperature.

$$COP \leq \frac{T_C}{T_H - T_C} \qquad \text{(eq. 1) [12]}$$

The COP of a refrigerator may be 4-10, whereas the COP of a TEM is an order of magnitude less [13]. This is due mainly to the negative effects of joule heating. The equation shown below models the heat absorbed into the TEM, expressed as $Q_C$.

$$Q_C = SIT_C - K(T_H - T_C) - \frac{1}{2}I^2R \qquad \text{(eq. 2) [14]}$$

The first term in this equation represents the Peltier effect. The second term represents the resistivity of the TEM due to conduction (an inherent property), and the third term represents joule heating [15]. Increasing the amount of current eventually causes the third term to dominate, reducing the cooling and lowering the COP. With regard to the application in the payload, supplying too much current will reduce the temperature difference the TEM can achieve. Testing for the optimal current required to achieve the greatest temperature difference is explained in *Section 7.2.2*.

Another example of active cooling is a vapor-compression refrigeration system. Although generally more efficient than a TEM, these refrigeration systems are bulky mechanical systems that may require costly maintenance. The combined weight of refrigeration system components is much greater compared to the typical 0.04 kg mass of a TEM. TEMs also have a very small form factor and they can be easily replaced. To improve TEM performance, two enhancements were added to the design: insulation (Outer Insulation Subsystem) and heat dissipation. The heat dissipation components

[12] Borgnakke, Claus, and Richard E. Sonntag. Fundamentals of Thermodynamics. New Jersey: Wiley, 2012. Print.

[13] Francis, Onoroh, Chukuneke Jeremiah Lekwuwa, and Itoje Harrison John. “Performance Evaluation of a Thermoelectric Refrigerator.” International Journal of Engineering and Innovative Technology 2.7 (2013): 18-24. Web.

[14] Lee, Hohyun. (2014). Santa Clara University, Santa Clara, CA.

[15] Ibid.

consist of a heat sink and fan, providing forced convection to improve TEM heat rejection.

### *3.2 Heat Dissipation*

The heat sink and fan work in tandem to improve the performance of the TEM. The heat sink conducts the rejected heat from the TEM hot side through the fins. These fins increase surface area while maintaining the cross-section, increasing the effectiveness of the fan's forced convection. The fan intake and two exhaust channels are exposed on the bottom of the payload so that ambient air from outside the UAV can travel through the system. A cross-section of this ventilation illustrating the airflow is shown below in *Figure 5*.

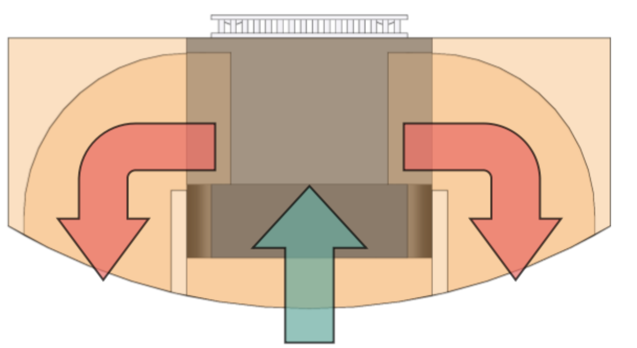


***Figure 5:*** Cross-section of the ventilation showing the direction of airflow.

In order to improve the heat dissipation effectiveness, the heat sink and fan were selected using data from a set of experiments. These experiments are outlined in *Section 7.2.1*. Both of these components are commercially available.

### *3.3 Inner Chamber*

The inner chamber of the payload is made up of two 6061 aluminum blocks machined using a vertical mill. These blocks have three holes each, sized to fit vaccine vials in one and blood sample vacutainers in the other. They are designed so that, when stacked together, heat is removed from the middle of the assembly. The aluminum is shown below in *Figure 6*.

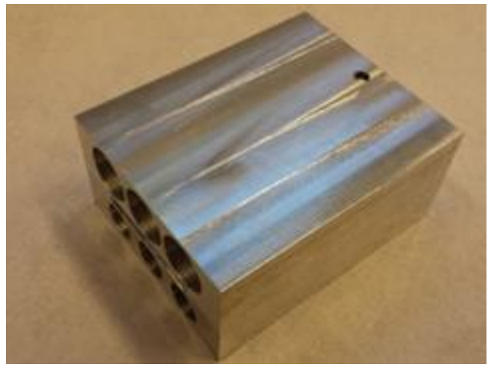


***Figure 6:*** Inner Chamber aluminum blocks stacked together.

Aluminum has a high thermal conductivity, allowing for a uniform temperature gradient throughout the material and an effective removal of heat. Using aluminum as the medium for conductive heat transfer allows the Heat Removal Subsystem components to work together effectively. For ease of manufacturing, the blocks are machined as two separate pieces. Once joined together, there is high potential for air pockets between the machined faces. To improve the thermal conductivity between the two blocks, thermal interface material is used. This subsystem utilizes Laird Tflex™ 720. This putty-like material is in the form of a thin sheet, and possesses a thermal conductivity of 5 W/m·K, which is greater than air [16,17].

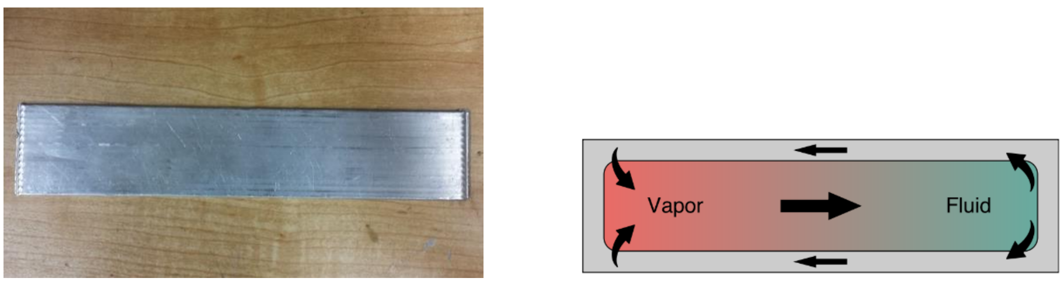
### *3.4 Planar Heat Pipe*

The performance of the TEM depends on the effectiveness of insulation and heat dissipation components, both of which take up physical space. In order to maintain a small payload cross-section while accommodating these components, the design utilizes a planar heat pipe. This component relocates the transfer of heat from the inner chamber to the TEM such that neither the insulation nor heat dissipation is compromised. Additionally, the heat pipe allows for greater distance between the inner chamber and the TEM, decreasing the potential for heat to cycle back into the subsystem.

[16] "Tflex™ 700 Series." Laird Technologies, July 2014. Web. http://www.lairdtech.com/brandworld/library/THR-DS-TFlex-700_07_2_14.pdf.

[17] Bergman, Theodore L., David P. Dewit, Adrienne S. Lavine, and Frank P. Incropera. Fundamentals of Heat and Mass Transfer. New Jersey: Wiley, 2011. Print.

Heat pipes are heat transfer devices commonly used in laptops and televisions that operate on two principles: thermal conduction and phase transition. The working fluid inside the heat pipe condenses as it travels from the inner chamber end to the TEM end and evaporates as it travels back to the inner chamber end. Heat pipes are effective heat transfer components due to the high thermal conductivity that boiling and condensing points possess. The heat pipe used in the payload design has an effective thermal conductivity of approximately 3000 W/m·K [18]. The functionality of the planar heat pipe is shown below in *Figure 7b*, where heat is transferred from the red end to the blue end.

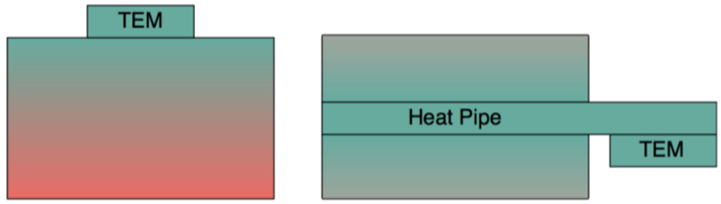



***(a)*** ***(b)***

***Figure 7:*** Aluminum planar heat pipe (a) and heat transfer schematic (b).

The heat pipe is located through the middle of the inner chamber to ensure uniform heat dissipation through either side of the subsystem. This aspect of the design also validates the use of a heat pipe since the TEM can be placed only on an external face. Placing the TEM directly on the inner chamber material does not guarantee this same level of uniformity that a heat pipe through the middle provides. The temperature gradient from one side of the aluminum to the other will be greater without the use of a heat pipe, which could affect vaccine safety. Using a heat pipe cuts the effective material thickness in half, as shown in *Figure 8*.

[18] Ibid.




***(a)*** ***(b)***

***Figure 8:*** Inner Chamber temperature gradient comparison without heat pipe (a) vs. with heat pipe (b). Temperature gradient ranges from blue (cold) to red (hot).

## Chapter 4 – Outer Insulation Subsystem

### *4.1 Expanded Polystyrene Foam*

The Outer Insulation Subsystem protects the inner chamber from the ambient temperatures that can exceed 40 °C. This subsystem is constructed using expanded polystyrene (EPS) foam because it has a high thermal resistivity in addition to being lightweight and inexpensive. The EPS foam, shown in *Figure 9* below, is cut into panels manually using a hot wire foam cutter.

***Figure 9:*** EPS foam panel.

The panels are bonded with Loctite PL Premium Polyurethane Construction Adhesive. The dimensions for the EPS foam were determined based off of 3D shape factor calculations. Using the known properties of the EPS foam and the desired temperature difference through the walls, we determined that a wall thickness of 25.4 mm (1 in.) would require just under 2 W of cooling. These calculations are provided in *Appendix A.5*. Based on prior student research, the electric power required by a TEM is close to ten times the cooling power, and this value is acceptable for our design. Additionally, a 1 in. thickness is very easy to manufacture. This thickness is used for all insulation faces except for the front and curved bottom. The front thickness is 50.8 mm (2 in.) due to the excess length of the planar heat pipe. The bottom of the insulation follows the curved profile of the fuselage, in addition to the initial wall thickness.

### *4.2 Birch Plywood*

In addition to EPS foam insulation, the Outer Insulation Subsystem consists of a birch plywood shell. The plywood panels were laser cut and fastened with contact cement, as shown below in *Figure 10*.

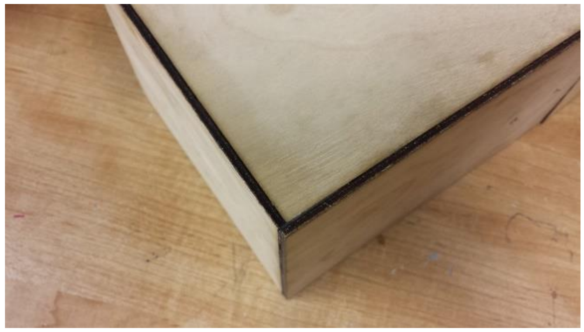


***Figure 10:*** Birch Plywood sample.

The main purpose is to provide structural rigidity for the otherwise soft EPS foam. This feature enables the use of latches to securely fasten the lid to the body of the payload, ensuring minimal heat loss. Additionally, the plywood shell accommodates the Temperature Control and Power Supply Subsystem components. Future design iterations will utilize a different material for this outer shell that can be manufactured into fewer separate pieces, reducing assembly costs.

## Chapter 5 – Temperature Control Subsystem

### *5.1 Feedforward Control Loop*

The Temperature Control Subsystem regulates the power delivered to the TEM, ensuring that the inner chamber is maintained within the correct temperature range. This is achieved using a feedforward control loop. Most control systems are based on a feedback control loop or model predictive control. Both of these control loops can be complex due to the nature of the dynamic systems they are often implemented in. One of the most common control loops is the proportional-integral-derivative (PID) controller. This controller relies on current, past, and anticipated error to adjust the system [19]. The payload does not use a PID controller to regulate the power because this process requires too much time to correct the temperature. This is discussed further in *Section 7.2.2*. Instead, a very basic feedforward loop uses the temperatures of the environment and inner chamber to switch between two operation modes.

Based on TEM tests discussed in *Section 7.2.2*, it is evident that the TEM does not require the optimal current value since the ambient temperature is not always 40 °C. The feedforward loop switches between two modes, Full Power Mode and Power Saving Mode, depending on the ambient temperature. Full Power Mode is based on the optimal current value for a 32 °C temperature difference, and Power Saving Mode is based on the power required to maintain a 20 °C temperature difference (28 °C ambient temperature and internal temperature of 8 °C). When the ambient temperature is detected to be greater than 28 °C, Full Power Mode is activated. Otherwise, Power Saving Mode is activated. In addition to the ambient temperature, the feedforward loop is also influenced by the temperature of the inner chamber. If the temperature of the inner chamber falls to 4 °C, the power is turned completely off. When the inner chamber temperature is above 6 °C, the power is turned on depending on the ambient temperature. These boundaries have been set based on tests discussed in *Section 7.2.4*. The feedforward loop results in a slight temperature oscillation inside the inner chamber that is within the 2-8 °C range due to the power-saving on-off characteristic. It also saves power by switching between two different operating powers.

[19] Nise, Norman S. Control Systems Engineering. New Jersey: Wiley, 2011. Print.

### *5.2 Components*

The temperature controller utilizes an Arduino microcontroller, two buck converters, two relays, and two temperature sensors. The adjustable DROK® buck converters step down the power from the single Power Supply Subsystem source for each operating mode. One buck converter adjusts the voltage to 12 V for Full Power Mode. The Arduino Micro is also powered from this output. The other buck converter adjusts the voltage to 8 V based on TEM test results. Both of these powers are connected to the TEM with AZ830 relays in between. These are used as on-off switches controlled by the Arduino based on the TMP 36 temperature sensor readings. One sensor is exposed to the ambient environment and the other is exposed to the air inside the inner chamber. The components are soldered and wired together on a perfboard, and housed within a 3D printed enclosure. XT60 connectors join the relay outputs to the TEM and the buck converter inputs to the Power Supply Subsystem. A schematic of the components and their interaction in the control system is shown below in *Figure 11*.

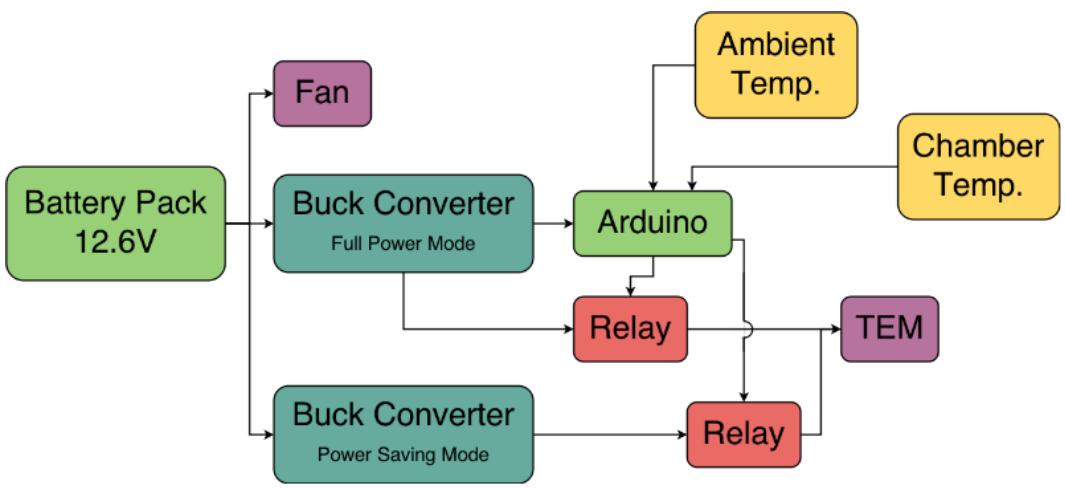



***Figure 11:*** Feedforward loop component schematic.

## Chapter 6 – Power Supply Subsystem

### *6.1 Lithium-Ion Batteries*

The power supply subsystem consists of NCR18650b lithium-ion battery cells. Each cell has a capacity of 3.4 Ah and a fully charged voltage of 4.2 V. These cells have a high energy density and have built in protection from over-discharge and overcharge. The lithium-ion batteries power the TEM, fan, and Temperature Control Subsystem components. The cells are arranged in such a way that supplies the output voltage required by the TEM with a 10-hour discharge capacity. In order to have an output voltage of 12 V that is needed by the TEM, 3 cells are arranged in series. To increase the capacity for 10 hours of operation, 5 of these 3-series configurations are arranged in parallel. The 15 lithium-ion cells are packaged in a 3D printed battery housing, shown below in *Figure 12*.

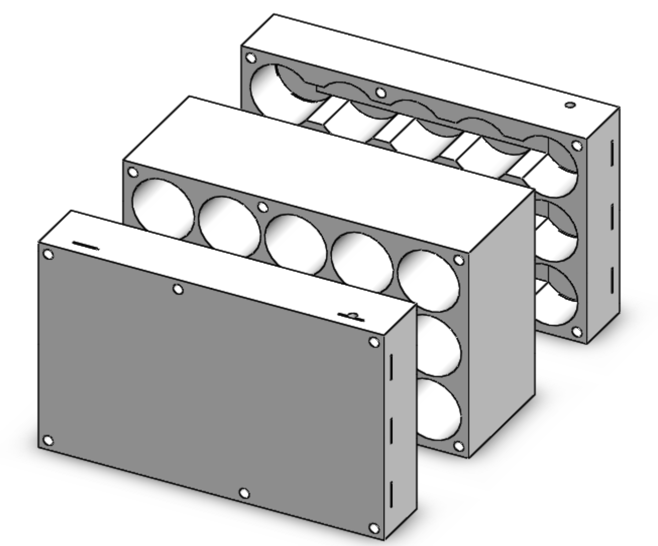


***Figure 12:*** Components for the 3D printed battery housing.

Nickel solder tabs and springs are used to achieve the parallel and series configurations. Two wires exit the housing and are attached to an XT60 connector compatible with the Temperature Control Subsystem.

## Chapter 7 – System Integration and Testing

### *7.1 Thermal FEA Simulation*

The purpose of the thermal finite element analysis simulation was to observe how the subsystems interact in terms of thermal loads and heat transfer. The subsystems included in the simulation are the Outer Insulation and Heat Removal Subsystems. Our team decided to use SolidWorks Simulation software since we already modeled the payload using SolidWorks. By modeling the temperature distribution inside our system, we observed how heat is removed from the inner chamber. These simulations can be compared to simplified hand calculations based on the same parameters in *Appendix A.5*. The model we analyzed is from February and does not include the Temperature Control or Power Supply Subsystems because they do not have much effect on the payload in terms of direct heat transfer. The Outer Insulation and Heat Removal Subsystems are the most important subsystems to model because they directly facilitate the heat transfer.

#### *7.1.1 Model Parameters*

Several assumptions were made in order to simplify and analyze our system with SolidWorks Simulation. These include the modeling materials, geometries, and external environment properties. The materials used in this model are consistent with the materials used in the prototype iteration. Material properties are based on defaults in the SolidWorks materials library, and some have been added into custom materials. The Outer Insulation Subsystem is made up of EPS foam with a thermal conductivity of 0.033 W/m·K. The inner chamber is made up of 6061-T6 aluminum alloy with a thermal conductivity of 170 W/m·K. The heat pipe is a custom material with a thermal conductivity of 3000 W/m·K. Between the aluminum pieces and heat pipe are strips of thermal interface material, each with a thermal conductivity of 5 W/m·K.

In order to conduct the thermal analysis, we simplified our model for the ease of understanding the concept of heat removal from the inner chamber. Although the foam panels are bonded together with a polyurethane-based adhesive, they were simplified to a single, uniform structure in the model. The aluminum blocks did not have holes for the threaded fasteners that secure them together. To model the heat removal through the heat pipe, a simplified TEM “block” was added to the model with the same properties as the heat pipe. This provided a more accurate thermal plot as the heat removal was concentrated at the TEM side. The payload is normally housed within the SkyPort UAV fuselage, but for this model, it was fully exposed to the environment. This was due to the high complexities of the fuselage geometry as well as the thermal properties. The model was meshed in SolidWorks using standard mesh dimensions of 4.00 mm triangle size and 0.20 mm tolerance. Schematics of the simplified system and mesh can be found in *Appendix D.1*.

To simulate the environment that the payload is exposed to, the external environment applied to the model was 313.15 K (40 °C) with natural air convection (10 W/m$^2$·K). The exposed surfaces of the Outer Insulation Subsystem were subject to this environment. Based on the hand calculations, the power required to achieve a temperature difference of 40 °C between the inner chamber and the environment is approximately 1.935 W. In the model, this heat power was applied to the exposed bottom face of the TEM. The model with dimensions is shown below.

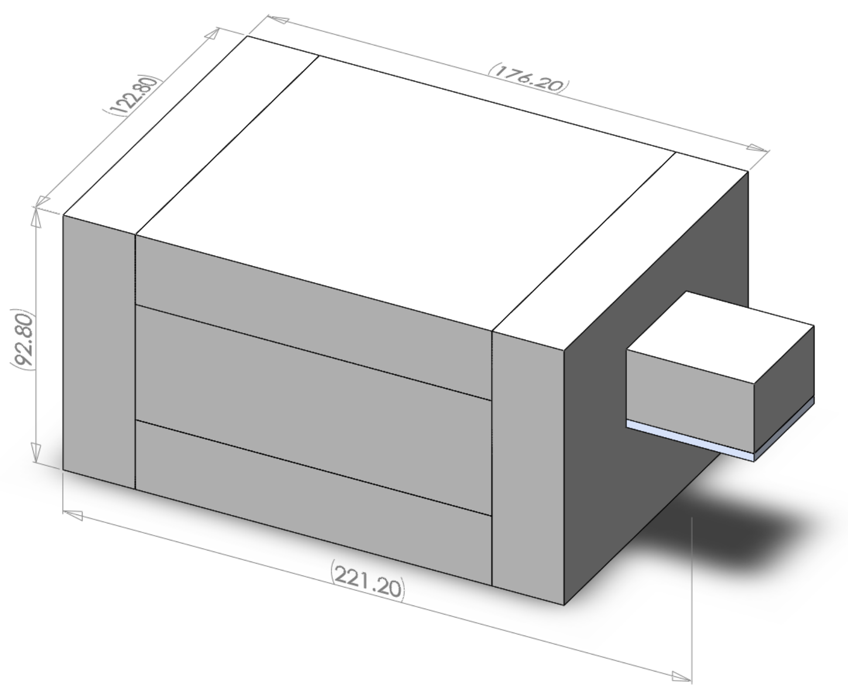



***Figure 13:*** Assembly of the simplified model with dimensions in millimeters.

### 7.1.2 Model Analysis

Based on the temperature distribution analysis, the simulation was very close to the calculated shape factor results. From our calculated results, it was determined we would need 1.935 W of heat to be removed to reach a temperature difference of 40 °C. In our simulation, it was assumed that we had a natural convection for air of 10 W/m$^2$·K and approximately 2 W of heat removal. Based on these inputs, we obtained a temperature difference of approximately 41 °C, which is very similar to our calculated value. *Figure 14* below shows the thermal plot of the payload model.

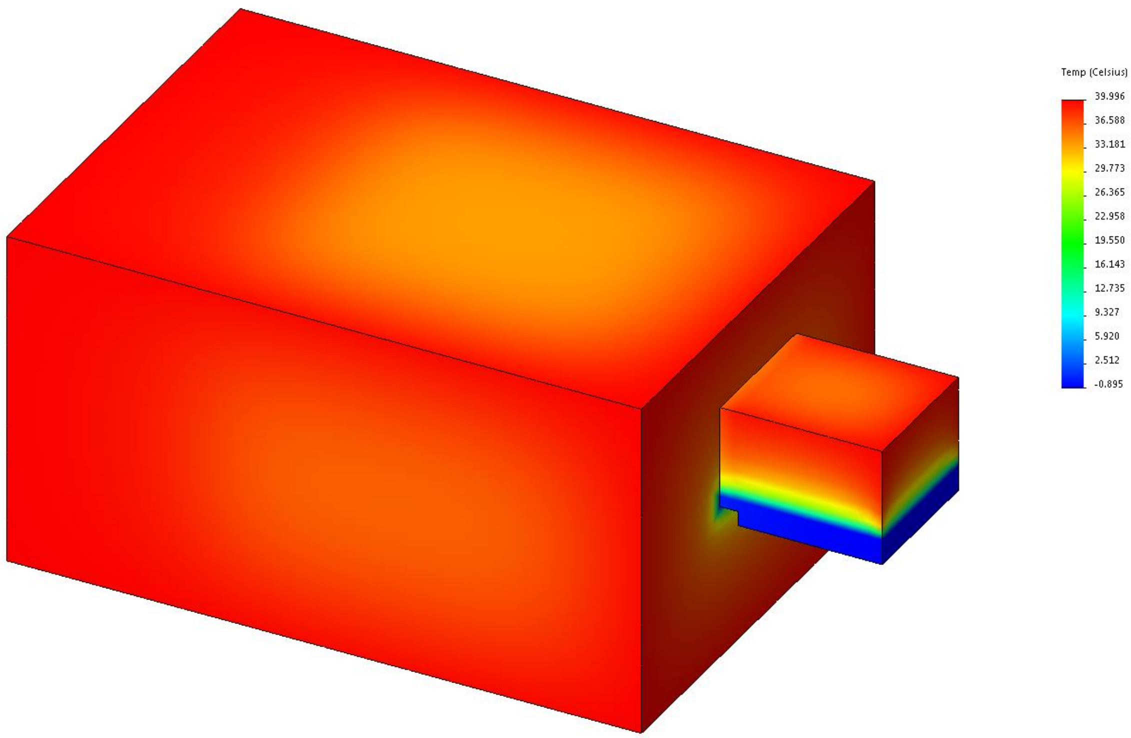



***Figure 14:*** Thermal plot of payload simulation with temperature ranging from 0 °C (blue) to 40 °C (red).

From our simulation, we also observed where the temperature is the highest and lowest inside the inner chamber. A cross-section of the simulation is provided below in *Figure 15*.

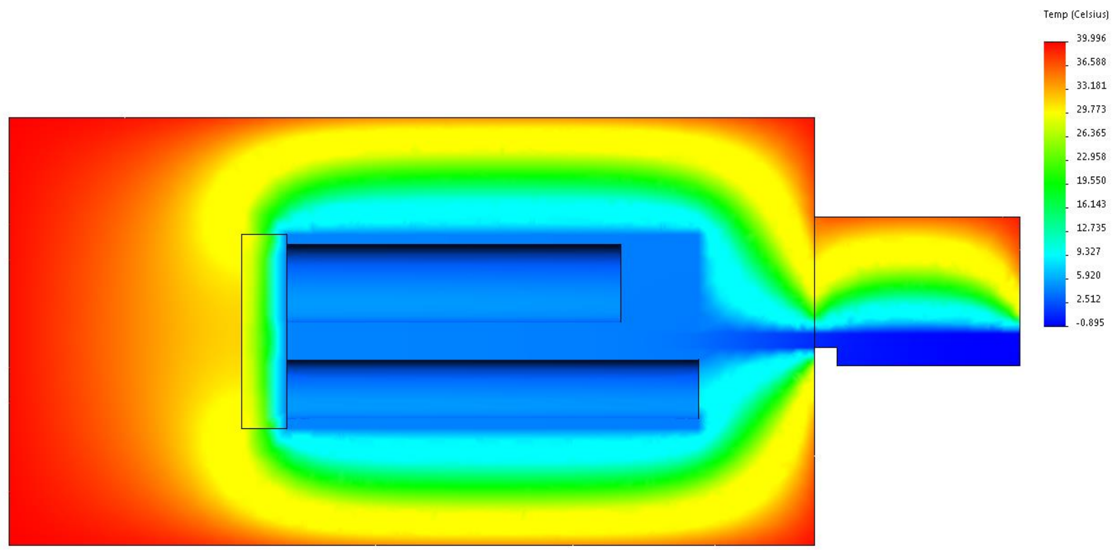



***Figure 15:*** Thermal plot of payload cross-section with temperature ranging from 0 °C (blue) to 40 °C (red).

The thermal plot shows that the temperature distribution within the aluminum components is relatively even. Additional thermal plots are provided in *Appendix D*.

Based on the results, we were able to see how much heat removal was required to reach the desired temperature difference. Using this software to do a thermal analysis, we proved that our calculated results are valid. Also, we proved that the thickness of the insulation provides enough resistance to prevent too much heat loss. However, due to slight variations in temperature on the outer faces of the Outer Insulation Subsystem, thicker insulation material may be beneficial in a future prototype iteration. Based on our thermal plot, we determined that the placement of the vials inside the cooling chamber is not a priority since there is a uniform temperature distribution within the aluminum components.

The SolidWorks Simulation software proved to be beneficial towards the completion of the project. However, we realized that there is much more work to be done in order to benefit significantly from the simulation. Since our team is inexperienced using this software, it was difficult to use this software to the best of its ability. Overall, this analysis helped us visualize how heat was being removed from the payload. The results validate our initial conduction shape factor calculations and show that the temperature distribution within the inner chamber is relatively uniform.

*7.2 Experimental Tasks*

It is evident that almost every aspect of the payload design can be changed to improve its performance. Each subsystem contains components that can be optimized, such as reducing the size of the inner chamber, changing the type of insulation, and changing the components of the Heat Removal Subsystem. Based on discussions with the other SkyPort teams, our team decided to keep the physical dimensions of the inner chamber and Outer Insulation subsystems at a fixed value. This decision allowed our team to focus on improving the performance of the Heat Removal Subsystem, and gave the other teams fixed dimensions for payload integration. This decision was also beneficial since the Power Supply and Temperature Control subsystem designs (i.e., the number of batteries) rely heavily on the Heat Removal Subsystem performance. The Power Supply Subsystem possesses a considerable amount of mass, which is a very sensitive parameter for the SkyPort teams. Maintaining a minimal mass is a critical parameter in the optimization of these subsystems.

In terms of the Product Design Specification chart (PDS), our team settled on an outer cross-section of approximately 130 mm wide by 96 mm tall, dictated by the vaccine capacity and insulation thickness. This design allows for a maximum of 6 vaccines and 3 blood samples to be transported at a time. It also factors in an insulation thickness of 25.4 mm (1 in.) and plywood shell thickness of 3.175 mm (⅛ in.). The current PDS is included in *Appendix A.3*. Our team decided to test different heat sink/fan assemblies and TEMs in order to determine the required power for the payload. The important parameters acquired from these tests were the most efficient heat sink and fan combination, as well as the optimal current at which the TEM operates while creating the largest temperature difference. The next logical step in the experimental process was to test different battery configurations with the Heat Removal Subsystem to validate their effectiveness and capacity. Due to the large amount of time estimated to complete these experiments, our team decided to test the payload performance in the worst-case scenario environment (~40 °C ambient temperature) only after accumulating data from the previous tests in which the ambient temperature was the standard room temperature (~20 °C). Subjecting the payload to the high temperature environment for each test would have taken a significant amount of extra time for setup. Once feasible parameters for the

Heat Removal and Power Supply subsystems were established, our team implemented the Temperature Control Subsystem to evaluate the amount of power saved during operation. The components of this subsystem were determined by first conceptualizing the control mechanism. Since there were a few options in terms of hardware, tests were conducted to justify the most practical components for the subsystem. The Power Supply and Temperature Control subsystem implementations serve as a proof of concept and also help determine how much power is saved during operation, with the potential to decrease the number of batteries required to operate the payload.

### *7.2.1 Fan and Heat Sink Evaluation*

The first set of experiments involved comparing TEM performance with different heat sink and fan combinations. The goal of this test was to determine the heat sink and fan combination that yielded the lowest temperature attainable by the TEM and therefore the greatest heat dissipation. Instead of testing using the payload assembly, the heat sink, fan, and TEM were isolated, assuming that the comparative results from the combinations would be enough to determine the most efficient pairing. The setup is shown below in *Figure 16*.

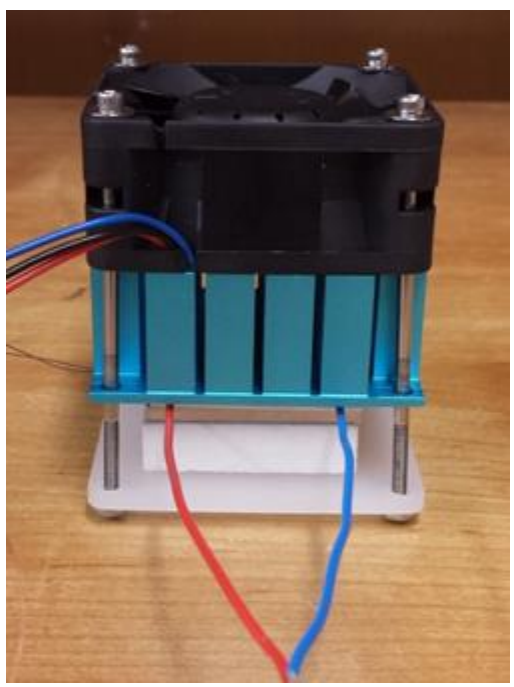


***Figure 16:*** Testing apparatus for heat sink and fan selection.

For these experiments, our team tested the performance of different fans at 12 V with a constant heat sink and TEM, and then different heat sinks with the best-performing fan and same TEM. We used LabVIEW and thermocouples wired to a compact data acquisition platform (cDAQ) to acquire TEM cold side temperature data for these tests. The fans selected for testing were 50 mm and 60 mm in size from brands such as CITYNET, Evercool, and Delta. They were powered by a constant 12 V from a DC power supply. The heat sinks selected for testing were of the same size range and from brands such as Aavid Thermalloy and ATS. The fan and heat sink models are shown below in *Figure 17* and *Figure 18*.

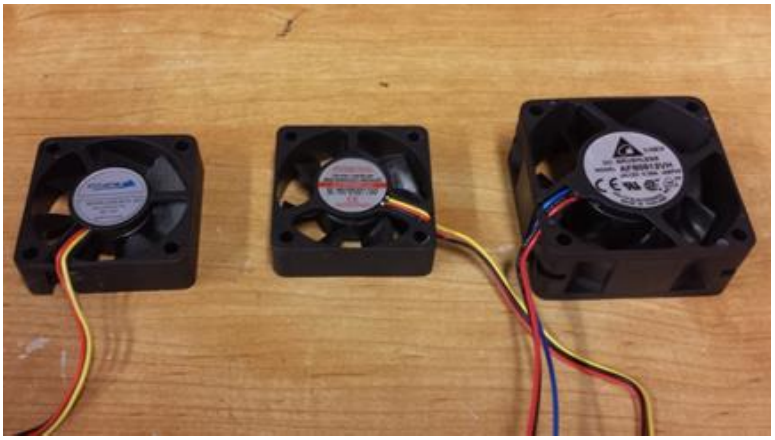


***Figure 17:*** Fans selected for performance evaluation. From left to right: CITYNET, Evercool, and Delta 60 mm. (Delta 50 mm not pictured)

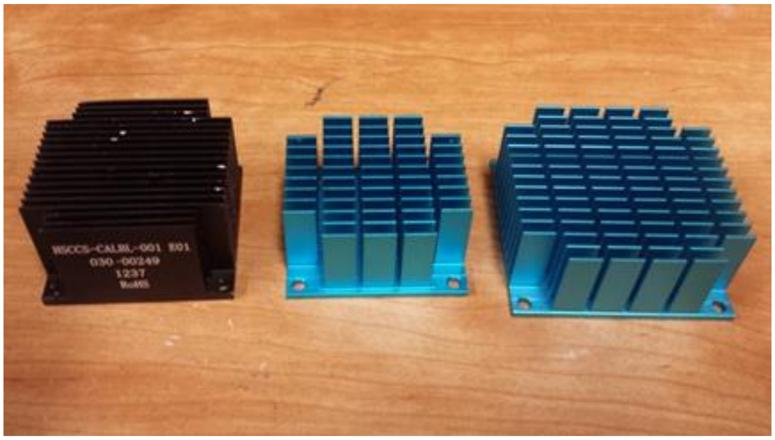


***Figure 18:*** Heat sinks selected for performance evaluation. From left to right: Aavid Thermalloy, blue 50 mm, blue 60 mm.

The current supplied by the DC power supply to the TEM was increased after the temperature of the cold side reached steady-state. The test concluded after the TEM temperature began to increase as a result of increased current, the point at which joule heating begins to dominate. The most efficient fan was determined by comparing the minimum cold side temperatures. Using this fan, the different heat sinks were tested with the same procedure in order to determine which combination yielded the highest heat dissipation performance. This combination consists of the Evercool fan and Aavid Thermalloy heat sink. Comparative results are shown below in *Table 1*.

***Table 1:*** Fan and heat sink effectiveness results.

| **Black 50 mm Heat Sink** | | **Blue 60 mm Heat Sink** | |
|---|---|---|---|
| **Fan Type** | **Temp. (°C)** | **Fan Type** | **Temp. (°C)** |
| CITYNET | -13.42 | Delta | -12.41 |
| Evercool | -14.47 | | |
| Delta | -12.3 | | |

| **Evercool Fan** | |
|---|---|
| **Heat Sink Type** | **Temp. (°C)** |
| Black 50 mm | -14.47 |
| Blue 50 mm | -4.64 |

These tests reveal that the Evercool fan and Aavid Thermalloy (black 50 mm) heat sink make up the most effective heat dissipation combination, since the TEM was able to achieve the lowest temperature of -14.47 °C.

It is possible to achieve greater heat dissipation effects with custom components. Such components would be designed specifically for the payload system. For example, graduate students have conducted research on heat sink fill factor characterization. This research is beneficial because it can allow our team to design a custom heat sink that performs better than the commercially available one our team is currently using.

### *7.2.2 Thermoelectric Module Evaluation*

Since TEM performance can vary in terms of power consumption and temperature difference based on the system they are implemented in, our team evaluated the different TEMs using a consistent payload assembly. While this increased the duration of the test significantly (in comparison to testing with only the Heat Removal

Subsystem components), it provided more accurate results as the testing environment was very similar to the actual payload. The payload assembly consisted of all components except for the birch plywood shell, Temperature Control Subsystem, and Power Supply Subsystem. The TEMs selected for evaluation were manufactured by Marlow Industries and Laird. These models were suggested based on graduate research involving analysis of the TEM working conditions and physical properties using numerical methods [20]. Some of these TEMs are shown below in *Figure 19*.

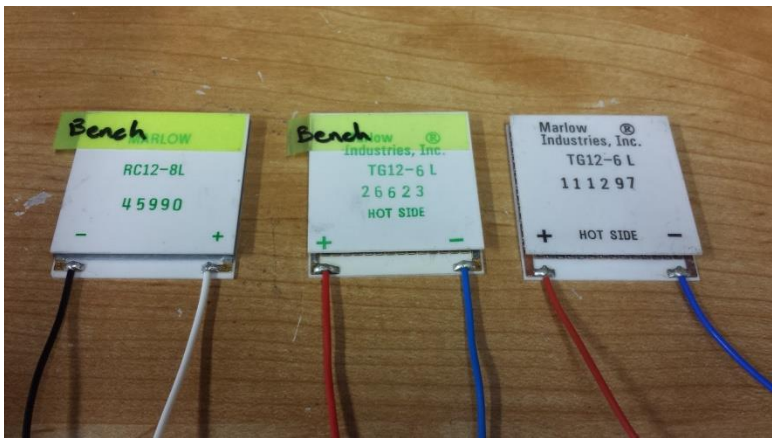



***Figure 19:*** Marlow thermoelectric modules selected for performance evaluation. From left to right: RC12-8L, TG12-6L, and TG12-6L (M).

Using the same data acquisition setup from the fan and heat sink tests, each TEM was evaluated to determine the optimal current required to reach the greatest temperature difference between the inside of the chamber and the ambient environment. Thermocouples were placed in water-filled vacutainers to observe the cooling behavior of a fluid within the chamber relative to the cooling of the chamber itself. Thermocouples were also placed on the chamber surface, vial opening air space, and the TEM cold side. For each TEM experiment, the same fan and heat sink combination was used, as well as a consistent 12 V delivered to the fan by the power supply. The setup is shown below in *Figure 20*.

[20] Gomez, Miguel, Rachel Reid, Brandon Ohara, and Hohyun Lee. “Investigation of the Effect of Electrical Current Variance on Thermoelectric Energy Harvesting.” *Journal of Electronic Materials* 43.6 (2013): 1744-751. Web.

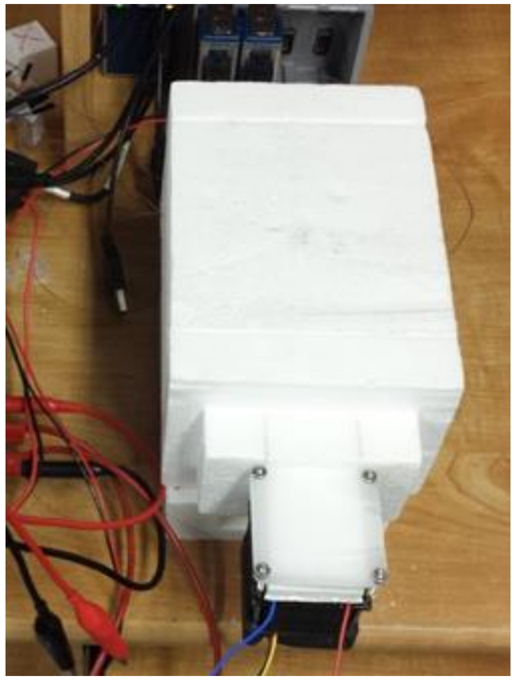


***Figure 20:*** Payload assembly used to evaluate TEM performance.

The LabVIEW VI was programmed to collect temperature data from each thermocouple and the voltage across the TEM, and the data was plotted over time. To evaluate the TEMs, the power delivered by the DC power supply was increased in constant current mode. This mode allowed for a stable output current in order to quantify the data accurately. With no known data about the TEM performance relative to the payload, the starting current was set to a relatively low value depending on the current rating of the TEM. The temperature graphs were used to determine when to increase the current; a relatively flat temperature slope indicated steady-state behavior. The current was increased in small increments, again depending on the current rating of the TEM as well as the temperature behavior. From previous experience in TEM optimal current testing, our team began each TEM test in the morning of a generally schedule-free day, knowing that each test could span over 6 hours. The test was concluded once the temperature began to increase as a result of an increased current, representing the joule heating threshold and the upper limit at which the heat sink and fan could dissipate heat. The plot below shows TEM temperature difference plotted against the required power.

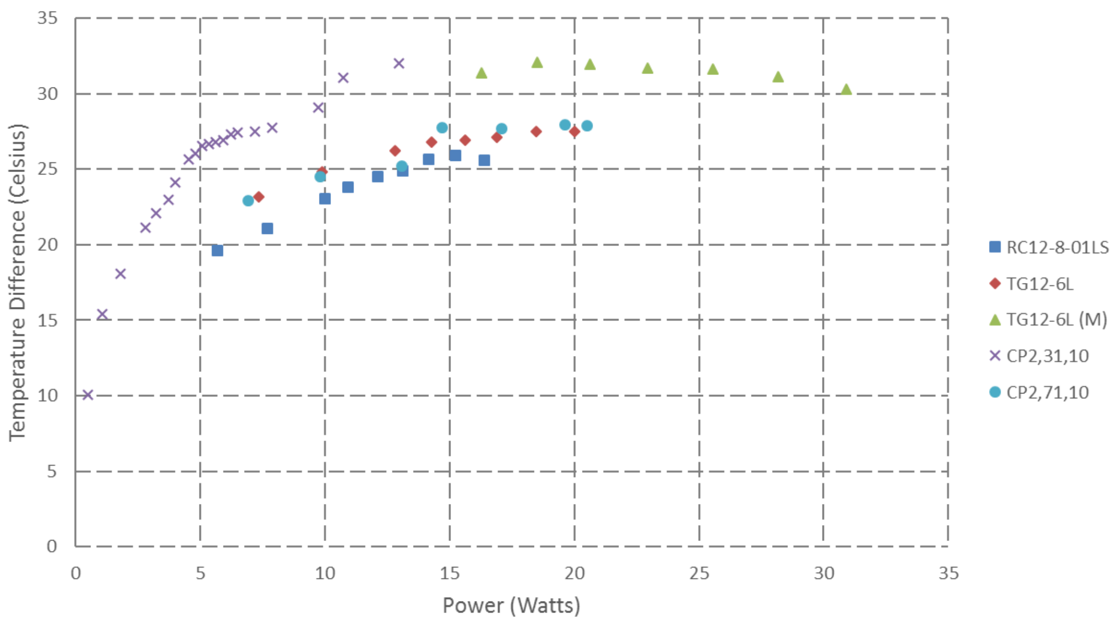



***Figure 21:*** Comparison of TEM performance.

From these tests, it is clear that the Marlow TG12-6L (M) and Laird CP2,31,10 models are suitable for the payload design since they can both achieve a temperature difference greater than 32 °C. This means that the inner chamber is capable of maintaining an 8 °C temperature while the ambient is 40 °C, which satisfies the payload design criteria. The TG12-6L (M) model requires about 18 W to achieve this temperature difference whereas the CP2,31,10 model requires about 12 W. *Table 2* and *Figure 22* below show the chamber temperature over time using the TG12-6L model.

***Table 2:*** TEM evaluation results for the TG12-6L model.

| Current (A) | Voltage (V) | Power (W) | Chamber Temp. (°C) | Time (Minutes) |
|---|---|---|---|---|
| 1.50 | 4.90 | 7.35 | -0.47 | 73 |
| 1.75 | 5.65 | 9.89 | -2.63 | 111 |
| 2.00 | 6.40 | 12.80 | -4.10 | 150 |
| 2.10 | 6.80 | 14.28 | -4.39 | 180 |
| 2.20 | 7.10 | 15.62 | -4.69 | 233 |
| 2.30 | 7.35 | 16.90 | -4.89 | 260 |
| 2.40 | 7.70 | 18.48 | -5.17 | 290 |
| 2.50 | 8.00 | 20.00 | -5.19 | 317 |

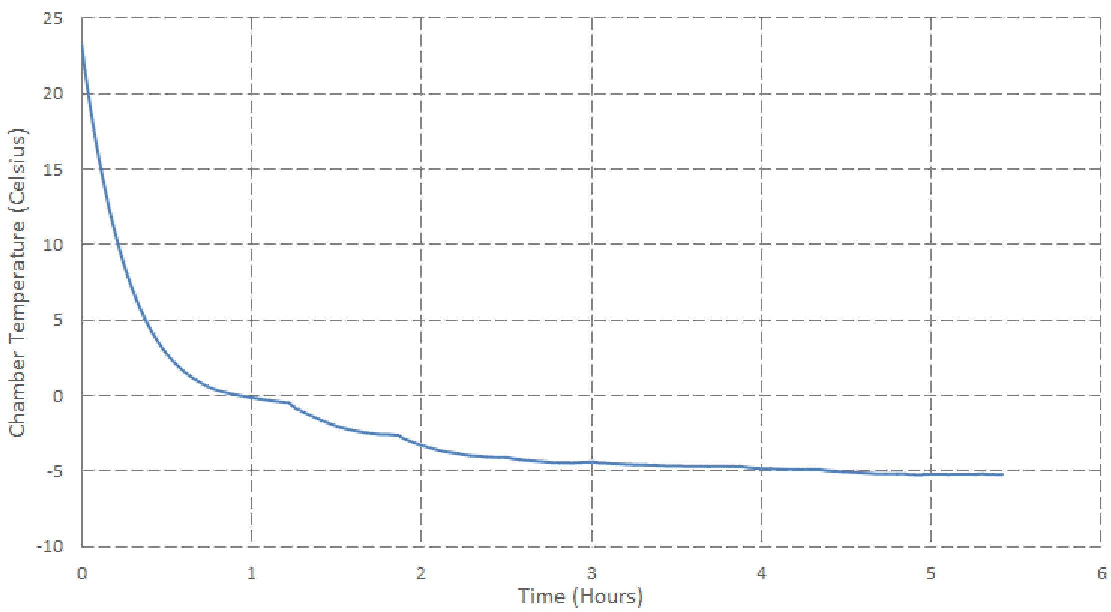



***Figure 22:*** Chamber temperature over time using the TG12-6L model.

The table shows voltage, power, chamber temperature, and steady-state time for the corresponding current level of the power supply. The plot visualizes the TEM cooling effect over time as the current to the TEM is increased. For this TEM model, it took almost 40 minutes to reach a steady-state temperature when the current was increased from 1.5 A to 1.75 A, and an additional 40 minutes from 1.75 A to 2 A. This behavior is the main reason why a feedforward control loop was utilized instead of a PID controller.

### *7.2.3 Battery Configuration*

To validate the battery configuration and observe the discharge behavior of the batteries, we kept the same setup from the TEM experiments and replaced the power supply with a 3-series-6-parallel configuration. Using the same LabVIEW VI, the voltage and current output by the batteries was monitored as well as the temperature of the payload. We also tested a 3-series-5-parallel configuration to compare discharge behavior and temperature differences. Ideally, the configuration with the least amount of batteries is ideal. Each configuration was tested continuously for 10 hours. Results are shown below in *Figure 23*.

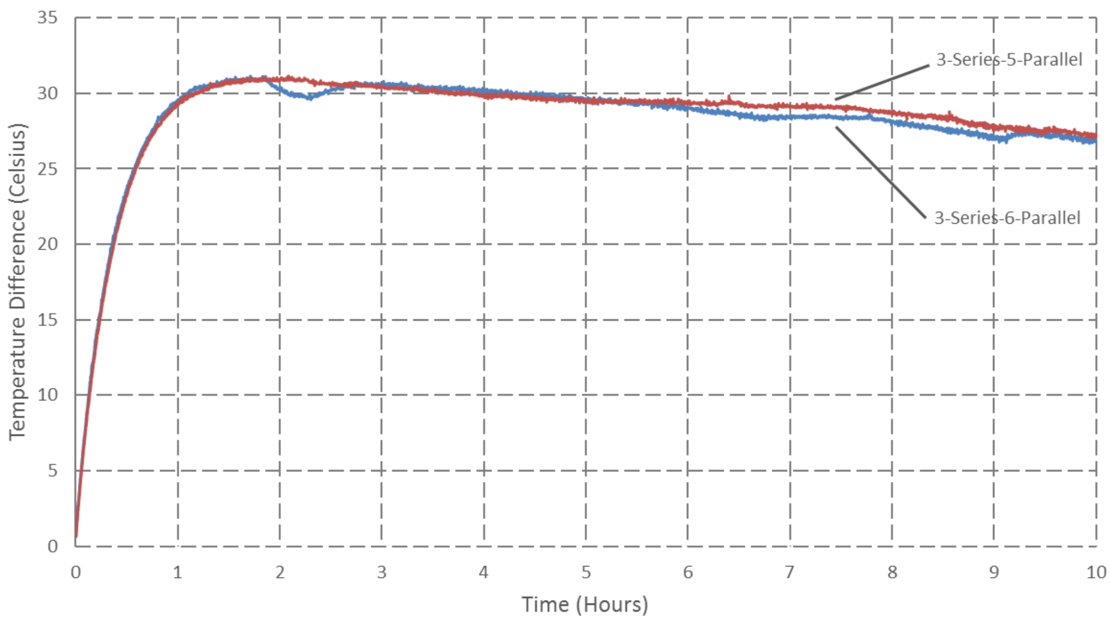



***Figure 23:*** Comparison of battery configuration performance.

From these graphs, it is evident that a 3-series-5-parallel configuration is ideal since it has the least number of batteries and still facilitates a large temperature difference for the entire test duration. The power consumption for this configuration is approximately 17.6 W. Combined with the Temperature Control Subsystem, the 3-series-5-parallel configuration will consume even less power.

### *7.2.4 Temperature Control Testing*

The Temperature Control Subsystem is a feedforward loop that switches between two power modes, called Full Power Mode and Power Saving Mode. This control loop utilizes the ambient temperature in order to device which power mode to use. In addition, the temperature of the chamber signals the system to turn off when the temperature reaches the lower bound (4 °C) and on for the upper bound (6 °C). Based on the design criteria, Full Power Mode operates at ambient temperatures above 28 °C while Power Saving mode operates at temperatures below 28 °C. The purpose of this control loop is to save power, since the TEM does not require the full power to operate at lower temperatures. To determine the amount of power consumed by the control system itself, each component was tested individually using a DC power supply and precision resistors. The results are tabulated below in *Table 3*.

***Table 3:*** Power consumption of each control system component.

| Component | Power (mW) |
|---|---|
| Arduino Micro | 500 |
| Buck Converters | 200 |
| Relays | 200 |
| **Total** | **900** |

From these tests, the control system consumes 0.9 W. This is a small amount compared to Full Power Mode. The buck converter from the batteries to the Arduino and Full Power Mode steps down the voltage from 12.6 V to 12.0 V, and the buck converter to Power Saving Mode steps down the voltage to 8 V. These voltages were determined based on the TEM tests in *Section 7.2.2*.

We implemented the Temperature Control Subsystem with the Power Supply Subsystem and testing apparatus to observe the control system and quantify the power reduction. By controlling the temperature environment for the ambient temperature sensor, both power modes were tested for functionality. For this test, each mode was initiated twice for a duration of five on-off cycles, as shown below in *Figure 24*.

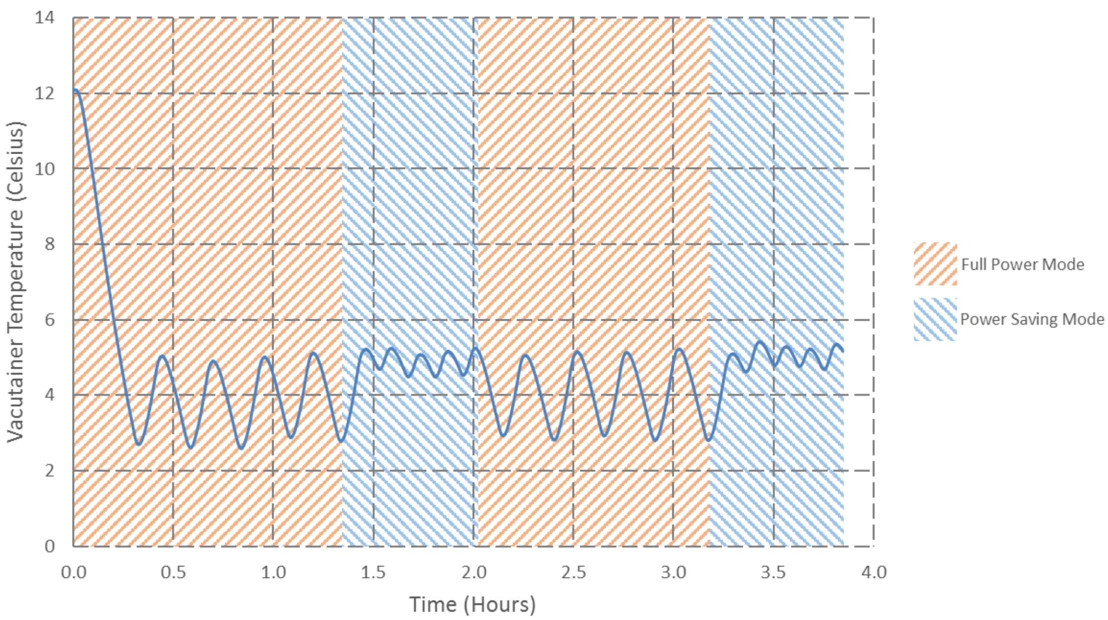



***Figure 24:*** Inner chamber temperature influenced by the Temperature Control Subsystem. Full Power Mode is shown in orange, Power Saving Mode is shown in blue.

This plot shows the temperature oscillations of the inner chamber as a result of each operating mode. Full Power Mode was initiated first, with resulting temperature oscillations between 3-5 °C. Power Saving Mode resulted in oscillations between 4.5-5 °C. The temperature bounds for both modes were set to 4 °C and 6 °C, and the discrepancy is attributed to the power distribution differences in the system resulting from each operating mode. The resulting power consumption with the Temperature Control Subsystem is 12.9 W, a 26.7% reduction from the 17.6 W consumed with full power and without the Temperature Control Subsystem.

## Chapter 8 – Cost Analysis

The SkyPort Payload Team applied for both the Roelandts Grant and the Santa Clara University School of Engineering Grant. The Roelandts Grant funded this project by providing $1600, and the School of Engineering funded this project by providing $1500, resulting in a total funding of $3100. A total of $3042 was spent on designing, building, and testing this project. The total amount spent for this project includes equipment for testing and manufacturing. The test equipment consists of a DC power supply, laptop, and cables, and the manufacturing equipment consists of a hot wire cutter.

The cost to fabricate one payload prototype was $300. A detailed table is provided in *Appendix B.1*. The total cost to build a single prototype is significantly higher than a production version because each component is based on the retail cost. Our team decided to manufacture parts of the payload by taking advantage of the equipment provided by the machine shop instead of having them manufactured by a company. By our team manufacturing some of the components for our payload, the total cost was reduced. The components that were manufactured by our team include the aluminum chamber, EPS foam, birch plywood, 3D printed electronic housing, and 3D printed battery housing. The aluminum chamber was fabricated using a vertical mill, the EPS foam was cut using a hot wire cutter, the birch plywood panels were fabricated using a laser cutter, and the Temperature Control and Power Supply subsystem housings were 3D printed. It can be seen from the table that the batteries contribute about 50% of the total cost for a single prototype. If our payload were to be mass produced, this amount would be significantly reduced by about $200. The components that would contribute to the reduction in the overall cost would be the aluminum, TEM, plywood, foam, latches, and thermal interface material.

## Chapter 9 – Engineering Standards and Realistic Constraints

As mentioned in *Section 1*, there are many factors that must be considered in order to successfully complete our project. These considerations go beyond the scope of this Senior Design Project and are applicable in the engineering field. As outlined in the *Santa Clara University Engineering Handbook*, a successful engineer is defined by many key aspects. The understanding and implementation of these aspects encourages lifelong learning. The underlying purpose of these engineering components is to improve the human condition while being mindful of the planet. Most of these are relatable to the humanities, such as sustainability, ethical, health and safety, and social considerations. Our design project is a product of these engineering characteristics.

### *9.1 Sustainability Considerations*

An engineering project can be sustainable in two ways. First, it refers to the degree to which the product can continue to be useful. This is often referred to as "sustainable engineering." Additionally, in a broader sense, engineering products have the ability to sustain communities in terms of resources and economy. These are known as "sustainable communities." These two sustainability types must be balanced in order to both improve the human condition and be mindful of global resources. It was important to consider both of these sustainability issues as a design team in order to produce a successful, practical product.

Our design was heavily influenced by sustainability considerations. In fact, the motivation of our project was partially based on humanitarian concerns. To ensure that basic human needs were universally met, we designed our payload in an attempt to improve healthcare. In addition, our design considerations were based on the goal of producing a sustainable product, both in terms of functionality and production. Our design reduces the amount of vaccines wasted due to incorrect storage and poor transportation infrastructure. From a production standpoint, we incorporated robust and effective materials such as EPS foam and aluminum to improve the longevity of the product itself. In addition to these considerations, there was also a level of constraint our team maintained. We took into account the possible effects our design can have on the environment, such as energy and material consumption. Our payload project is itself a subsystem of the SkyPort UAV, so the sustainability considerations carry over to the full system. Some of the design constraints such as size and weight have contributed to the sustainability of the system, since we minimized the power and material consumption of our design.

### *9.2 Manufacturability Considerations*

There are often many ways to manufacture a design concept. Parts can be manufactured using different processes and tools that produce the same result, such as metal extrusion or milling. Additionally, these tools can be used in different ways or with a different order of steps, such as changing the cutting tools or cutting steps with a mill. The manufacturability of parts can be optimized in many ways; some of these factors include simplifying by standardizing and reducing the number of parts, as well as designing for ease of fabrication. Many design characteristics influence the manufacturability such as safety, usability, and efficiency.

Our team considered these manufacturing issues during the scope of our project, but they were not heavily addressed compared to other considerations because they were not within our project goals. Rather, we designed a proof of concept model that can be improved upon in the future in terms of manufacturability. Our primary concerns for this year consisted of optimizing the efficiency of the payload cooling capabilities while considering the size and weight. We also brainstormed concepts to improve the user-friendliness and make sure that the customer needs were satisfied. However, there are many areas to improve such as the machining processes and general complexity of the current design. For example, in order to reduce production cost and time, the aluminum blocks can be extruded instead of milled. This factors into sustainability as well, because less material is consumed.

### *9.3 Ethical Considerations*

The topic of ethics is very broad but also very important. There are many ways to approach the ethical implications of a project. The subject of ethics is influenced by a combination of moral rights, fairness and justice, and the common good. It is important to recognize and address any ethical issues that surface in a project. The consideration of ethics is important to our project in many ways; our project motivation stems from a few ethical issues and we have worked on the project itself in an ethical manner.

By designing a medical cooler for use with a UAV, we addressed the issue that healthcare is not adequate in many places in the world. As stated in *Section 1*, we aimed to contribute to the development of vaccine transportation devices and logistics in order to improve healthcare on a global scale. In addition to addressing ethical issues, our team dynamics were also influenced by ethical ideals. We ensured that each team member developed a sense of ethical behavior in order to successfully complete our project. This behavior included making sure data and calculations were correct, and that any approximations or assumptions were appropriately validated. These moral qualities were necessary in order to maintain a general goodness and positivity for the team and the project.

### *9.4 Health and Safety Considerations*

The general health and well-being of humanity is, in some ways, the basis to the engineering considerations discussed within this thesis. Health and safety influences the sustainability, ethical, social, and even manufacturability considerations. It is related to engineering failures, improving the safety of tomorrow, and being able to account for unanticipated consequences.

As stated previously, our motivation for this project was to improve healthcare by improving vaccine transportation in undeveloped regions. This goal directly relates to health and safety considerations. In addition, the health and safety of everyone involved in the project was important to consider. For example, safe manufacturing and fabrication practices were implemented. We took care to follow all safety procedures in the machine shop as well as safety precautions related to other materials and equipment. This included ventilation when using the soldering iron and hot wire cutter. In addition, our device was designed to be safe to use, as it contains no moving mechanical parts that could create pinch points. The many degrees of safety are apparent in our senior design project.

### 9.5 Social Considerations

It is important to consider the social implications of our senior design project. These implications involve the role of developing technologies in society as well as the role of engineers in addressing social issues. Even though technology has its obvious benefits, it is important to consider any negative effects that the technology might leave on society. In addition, it is important to understand the role of the engineer in facilitating these issues.

These social considerations had an impact on our project. Although it is obvious that our goal was to improve healthcare, we also considered the future implications that this project could have. This social consideration was in tandem with the sustainability consideration. Although our project was designed to improve vaccine delivery, it could potentially lead to misuse of aerial transportation and then require laws or codes to be developed to regulate it. It was up to the members of our team to be aware of these possibilities in order to produce a final product that was safe and practical.

### 9.6 Arts

As part of satisfying the Santa Clara University Core Arts & Humanities requirements, members of this team have all contributed original drawings, sketches, and/or CAD models and drawings to this project. Below are listed a sampling of at least one such artifact, and a reference to it, for each of the team members.

***Table 4:*** Examples of art with description and location within the thesis, by team member.

| Team Member | Description | Location |
|---|---|---|
| Madison Gee | Subsystem component schematics | Figures 4, 5, 6, 9, 10 |
| | Thermal FEA models | Figures 15, 16, 17, Appendix D |
| | System level models | Appendix A |
| | Design drawings | Appendix C |
| Hector Lopez | Feedforward loop schematic | Figure 13 |
| | 3D shape factor calculations | Appendix A |
| | Electronic housing drawings | Appendix C |
| Victor Magaña | Battery housing drawings | Figure 14 |

## Chapter 10 – Conclusions

### *10.1 Overall Evaluation of Design*

The final payload we designed is able to maintain the inner chamber at 5 °C for at least 10 hours. Because the ambient temperature affects the performance of the heat removal system, the payload has two operating modes: power mode and power saving mode. These two modes help save power while still maintaining the desired temperature. The payload also saves power because the TEM is not constantly operating, a result of the control system's on-off characteristic. Because the design of the payload and fuselage of the UAV depend on the other, determining appropriate dimensions as well as ensuring a weight of under 3 kg were difficult tasks. However, the payload dimensions were finalized based on input from both the Airframe and Payload teams, and the resulting payload weight was determined to be 2 kg. Taking into account the design specifications set by SkyPort, our design concept is a viable solution that can be integrated into the SkyPort UAV system.

### *10.2 Future Improvements*

In order to develop a more refined payload, we have examined a few improvements that can be implemented with additional research. Our current design features a commercially available TEM. With more research in the field of TEM optimization, custom design parameters for a more effective TEM can be submitted to a company such as Laird or Marlow. These parameters would be partly based on the actual payload design. A custom TEM has the potential to save more power.

The Temperature Control Subsystem was constructed using a perfboard for prototyping purposes. However, this resulted in a design that was not aesthetically pleasing or effective, due to the large number of wires that were manually soldered. To improve these aspects, a printed circuit board can replace the perfboard. This would reduce the overall size of the subsystem and improve manufacturability and assembly. In addition, the components such as relays and converters can be customized to reduce their power draw and regulate temperature more effectively.

Overall, the payload could be improved for a better user interface. Some ideas that we brainstormed are visual aids such as LEDs and a display showing the internal temperature. This would notify the user of any potential error in the delivery, and can improve the effectiveness of the design in the long run. From a manufacturing perspective, a design that requires less human assembly would increase production rate and reduce costs. In terms of maintenance, an improved design that simplifies the replacement of any components is optimal.

### *10.3 Lessons Learned*

As a result of the Senior Design Project, our team realized that working through iterations is the best way to facilitate a successful outcome. It was important that the team progressed through multiple designs in order to test and fix any issues. Creating different prototypes allowed the team to move one step at a time, and ensured that tasks could be progressively accomplished. This process ensured that, by the Senior Design Conference presentation, a working prototype was ready for demonstration. Since SkyPort is comprised of separate teams focusing on separate designs, it was very important to maintain thorough communication. This ensured that each team understood the specifications and constraints and that the SkyPort UAV components could be successfully integrated. The team learned how important communication is in the development of a product.

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## Appendix A – Design Criteria

### *A.1 Customer Needs Table*

This table is an organized visual aid that clearly displays customer needs by category and importance. These needs provided a basis on which our team could brainstorm possible payload designs that could later be modified and optimized to fit more refined customer needs and SkyPort specifications.

***Table A.1:*** Prioritized customer needs with importance indicated by the number of *'s.

| | |
|---|---|
| **Payload complies with WHO regulations** | |
| *** | Payload maintains allowable temperature for vaccines (2-8 °C) |
| *** | Payload functions in ambient temperatures of up to 40 °C) |
| **Payload is compatible with the SkyPort UAV** | |
| *** | Payload weighs under 3 kg |
| *** | Payload is fully enclosed within UAV fuselage during flight |
| ** | Payload has a height and width under 90x90mm |
| **Payload can be delivered to rural villages for vaccine administration** | |
| *** | Payload is insulated to maintain cooling for up to 10 hours |
| ** | Payload stores at least 12 vaccines |
| * | Payload releases independently (without human interaction) upon arrival |

### *A.2 System Sketch*

A set of preliminary SolidWorks sketches containing the components of the payload are provided below. The dimensions of each component are not fully optimized; these illustrations are meant to show proof of concept.

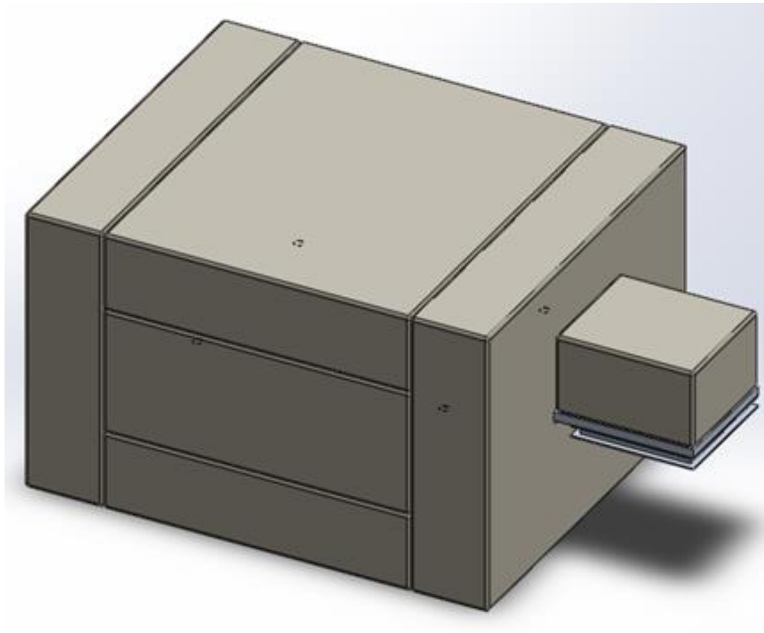


***Figure A.1:*** Concept sketch of the payload system including the inner aluminum chamber, outer insulation, heat pipe, and TEM.

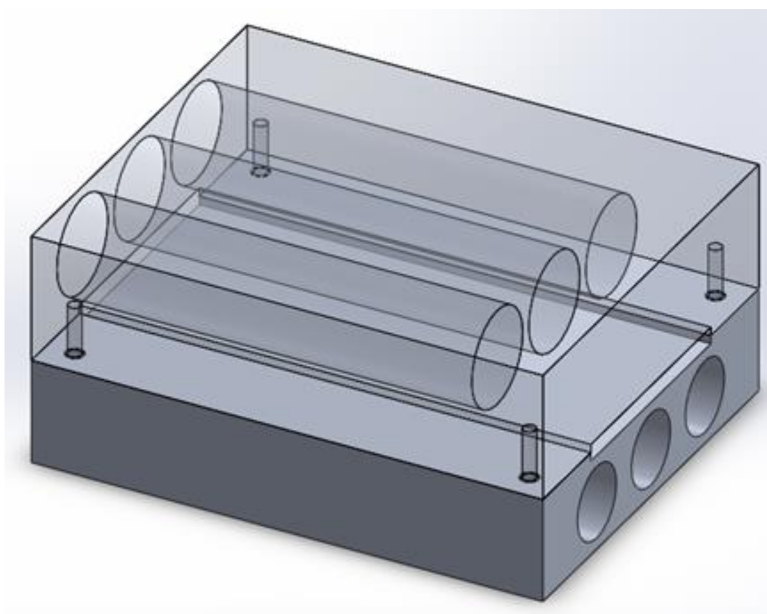


***Figure A.2:*** Concept sketch of the inner aluminum chamber with holes for the vials, vacutainers and heat pipe. Holes for the vials are in the upper, semi-transparent portion of the assembly.

### *A.3 Product Design Specifications*

The following table is a list of product design specifications based on parameters from a similar existing product. The product our team used to base our design off of is the

Last Mile Vaccine Cooler from the previous Senior Design year. This table was revised throughout the year based on our research and progress. This table was useful for brainstorming relevant design parameters and creating benchmarks for our design.

***Table A.2:*** Design specifications, revision 6.

| ELEMENTS/ REQUIREMENTS | UNITS | PARAMETERS | |
|---|---|---|---|
| | | DATUM | TARGET - RANGE |
| **Inner Chamber Subsystem** | | | |
| Internal Heat Transfer | N/A | Aluminum Conduction | Aluminum Conduction |
| Maximum Dimensions | Millimeters (LWH) | 90x72x42 | 90x72x42 |
| Vaccine Capacity | N/A | 6 Vials, 3 Vacutainers | 6 Vials, 3 Vacutainers |
| | | | |
| **Outer Insulation Subsystem** | | | |
| Maximum Dimensions | Millimeters (LWH) | 250x123x93 | 300x130x96 |
| Insulation Thickness | Millimeters | 25.4 | 25.4 |
| Shell Thickness | Millimeters | N/A | 3.175 |
| | | | |
| **Heat Removal Subsystem** | | | |
| Heat Pipe Length | Millimeters | 170 | 160 **OR** 172 |
| Cooling Power | Watts | 2 | 2 |
| | | | |
| **Power Supply Subsystem** | | | |
| Required Power | Watts | 10-20 | 10-20 |
| Number of Batteries | N/A | 18 | 12-20 |
| | | | |
| **Temperature Control Subsystem** | | | |
| Interior Temperature Range | Degrees Celsius | 2-8 | 2-8 |
| Duration of Cooling | Hours | 10 | 10 |
| | | | |
| **Miscellaneous** | | | |
| Weight | Kilograms | 3 | 2-2.5 |

### *A.4 Concept Scoring and Selection Matrices*

*Table A.3* consists of design parameters that our team considered. Each parameter was compared to another to produce a matrix. This matrix provided a basic comparison rating for each design parameter. From the results of this matrix, our team obtained better understanding of what to prioritize before devoting time to designing.

***Table A.3:*** Design parameter scoring matrix.

| | Criterion | 1 | 2 | 3 | 4 | 5 | 6 | 7 | SUM | FACTOR |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Weight | | 0.75 | 0.75 | 0.25 | 0.5 | 0 | 0.5 | 2.75 | 2.75 |
| 2 | Outer Dim. (insulation) | 0.25 | | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 1.75 | 1.75 |
| 3 | Inner Dim. (chamber) | 0.25 | 0.5 | | 0.25 | 0.25 | 0.25 | 0.25 | 1.75 | 1.75 |
| 4 | Temperature Range | 0.75 | 0.75 | 0.75 | | 0.75 | 0.75 | 0.75 | 4.5 | 4.5 |
| 5 | Machinability | 0.5 | 0.75 | 0.75 | 0.25 | | 0.75 | 0.25 | 3.25 | 3.25 |
| 6 | Cooling Duration | 1 | 0.75 | 0.75 | 0.25 | 0.25 | | 0.5 | 3.5 | 3.5 |
| 7 | Power Consumption | 0.5 | 0.75 | 0.75 | 0.25 | 0.75 | 0.5 | | 3.5 | 3.5 |

*Table A.4* consists of our team's preliminary designs, as well as an existing model to base them on. As with the PDS, this table uses the Last Mile Vaccine Cooler as the baseline. Each parameter from the previous table was rated from 0 to 5 based on how we believed they would impact the proposed design. Because our team had no hard data to justify these numbers, each parameter was set relatively in the middle and did not deviate to the extremes.

***Table A.4:*** Design concept scoring sheet.

| | TARGET or | DESIGN IDEAS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **CRITERIA** | **FACTOR** | **1 = Baseline** | | **Heat Pipe Sandwich** | | **Heat Pipe on Top** | | **Circular** | | **Pipes** | |
| Time – Design | 18 | 18 | | 10 | | 10 | | 15 | | 20 | |
| Time – Build | 18 | 18 | | 20 | | 20 | | 22 | | 25 | |
| Time – Test | 15 | 15 | | 10 | | 10 | | 10 | | 12 | |
| **Time Score** | 10 | | 10 | | 7.78 | | 7.78 | | 9.07 | | 11.00 |
| Cost – Prototype | 1150 | $ 1,150.00 | | $ 1,000.00 | | $ 1,000.00 | | $ 1,200.00 | | $ 1,300.00 | |
| Cost – Production | 700 | $ 700.00 | | $ 500.00 | | $ 500.00 | | $ 600.00 | | $ 650.00 | |
| **Cost Score** | 10 | | 10 | | 7.92 | | 7.92 | | 9.50 | | 10.30 |
| Weight | 2.75 | 3 | 8.25 | 2.5 | 6.875 | 2.5 | 6.875 | 2 | 5.5 | 3 | 8.25 |
| Outer Dim. (insulation) | 1.75 | 3 | 5.25 | 2 | 3.5 | 2 | 3.5 | 2 | 3.5 | 3 | 5.25 |
| Inner Dim. (chamber) | 1.75 | 3 | 5.25 | 2 | 3.5 | 2 | 3.5 | 2 | 3.5 | 3 | 5.25 |
| Temperature Range | 4.5 | 3 | 13.5 | 4 | 18 | 3 | 13.5 | 4 | 18 | 4 | 18 |
| Machinability | 3.25 | 3 | 9.75 | 2 | 6.5 | 2 | 6.5 | 1 | 3.25 | 0.5 | 1.625 |
| Cooling Duration | 3.5 | 3 | 10.5 | 3 | 10.5 | 2.5 | 8.75 | 2.5 | 8.75 | 2.5 | 8.75 |
| Power Consumption | 3.5 | 3 | 10.5 | 3 | 10.5 | 2.5 | 8.75 | 2.5 | 8.75 | 3 | 10.5 |
| | **TOTAL** | | 63.0 | | 63.7 | | 55.7 | | 52.7 | | 56.3 |
| | **RANK** | | | | | | | | | | |
| | **% MAX** | | 98.9% | | 100.0% | | 87.4% | | 82.7% | | 88.5% |
| | **MAX** | 63.7 | | | | | | | | | |

## *A.5 Calculations*

Included are preliminary calculations for the cooling schematic. These calculations approximate the amount of cooling power required to maintain the internal temperature of the payload at 2 °C assuming that the external temperature is 40 °C. 1.935 W is required to maintain a 38 °C temperature difference. This 3D heat transfer analysis is simplified in terms of the external temperature gradient. It also does not factor in the variable ambient air velocities or radiation.

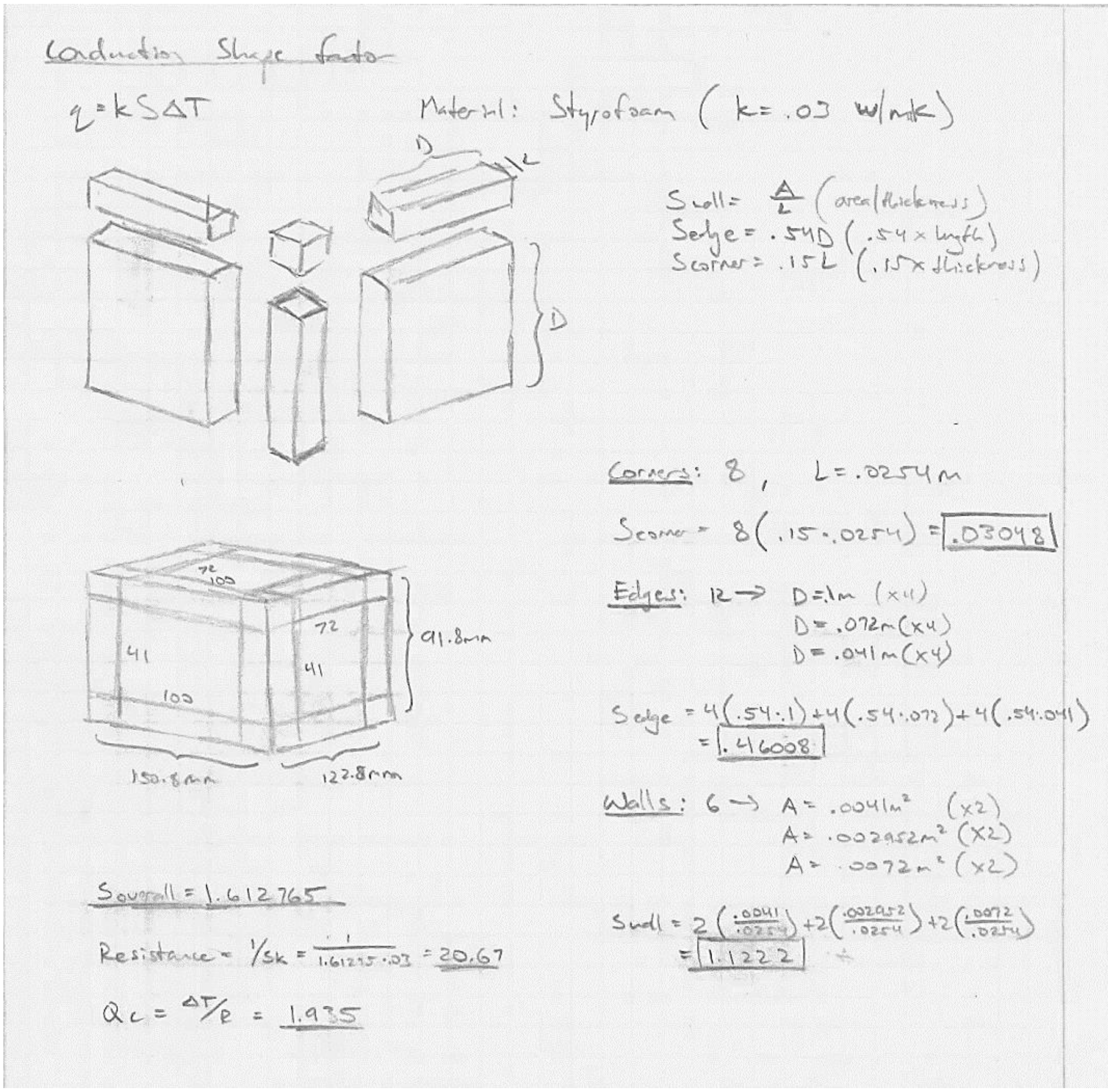



***Figure A.3:*** 3D shape factor calculations.

# Appendix B – Project Management

## *B.1 Budget*

***Table B.1:*** Cost to fabricate one prototype.

| Components | Quantity | Volume (in³) | Cost per Volume($/in³) | Price Per Piece | Total($) |
|---|---|---|---|---|---|
| **Insulation/Outer Shell** | | | | | |
| EPS Foam | N/A | 238.26 | 0.0023 | N/A | $0.54 |
| Birch Plywood | N/A | 40.25 | 0.0769 | N/A | $3.10 |
| Latch | 2 | N/A | N/A | $6.02 | $12.04 |
| | | | | | |
| **Heat Removal** | | | | | |
| Aluminum | N/A | 17.83 | 0.7682 | N/A | $13.70 |
| Heat Pipe | 1 | N/A | N/A | $1.00 | $1.00 |
| Heat Sink | 1 | N/A | N/A | $6.54 | $6.54 |
| TEM, TG12-6L | 1 | N/A | N/A | $40.00 | $40.00 |
| Fan | 1 | N/A | N/A | $10.00 | $10.00 |
| Thermal Interface Material | N/A | 0.6248 | 24.21 | N/A | $15.12 |
| | | | | | |
| **Power Supply** | | | | | |
| NCR18650b | 15 | N/A | N/A | $9.48 | $142.20 |
| | | | | | |
| **Temperature Control** | | | | | |
| Relay | 2 | N/A | N/A | $1.26 | $2.52 |
| Buck Converter | 1 | N/A | N/A | $9.00 | $9.00 |
| Arduino Micro | 1 | N/A | N/A | $21.00 | $21.00 |
| | | | | | |
| | | | | Subtotal | $276.76 |
| | | | | Sales Tax, 8.75% | $24.22 |
| | | | | **Total** | **$300.98** |

Sources: www.digikey.com, www.onlinemetals.com, www.mcmaster.com, www.sparkfun.com, www.homedepot.com

***Table B.2:*** Total budget.

| Income | | | |
|---|---|---|---|
| **Category** | **Source** | **Sought** | **Committed** |
| Grant | School of Engineering | $4,192.00 | $1,500.00 |
| | Roelandts | $4,192.00 | $1,600.00 |
| | **TOTAL** | **$8,384.00** | **$3,100.00** |
| **Expenses** | | | |
| **Category** | **Description** | **Quantity** | **Spent** |
| Insulation/Outer Shell | Styrofoam, Glue, Pen, Knife | 1, 1, 1, 1 | $41.21 |
| | Hot Wire Foam Cutter | 1 | $140.33 |
| | Latches | 12 | $46.98 |
| | Screws | 32 | $5.40 |
| | Birch Plywood, Glue | 2, 1, 1 | $36.72 |
| | BungeeSstrips, Velcro, Wood Screws | 1, 1, 2 | $9.80 |
| | Loctite Adhesive | 1 | $11.42 |
| | Birch Plywood, Glue | 1, 1 | $18.08 |
| Heat Removal | Aluminum Bar | 2 | $106.49 |
| | Thermal Interface Material | 1 | $127.57 |
| | TEMs | 7 | $315.50 |
| | Screws | 16 | $5.25 |
| | Heat Sinks, Fans | 2, 2 | $58.38 |
| | Precision Resistors, Fans | 10, 4 | $259.33 |
| | Thermal Tape | 2 | $60.66 |
| | Evercool Fans | 2 | $17.00 |
| Power Supply | Batteries, Chargers, Fan | 12, 2, 1 | $154.35 |
| | DC Power Supply, Banana Cables | 1, 1 | $225.52 |
| | Fan Screws, Washers, Nuts | 8, 8, 8 | $17.40 |
| | Heat Shrink Wrap, XT-60 connectors, 16 AWG Wire | 2, 2, 2 | $28.23 |
| | Spring Connectors | 5 | $12.27 |
| | Electrical Tape | 2 | $3.64 |
| | Solder Tabs | 50 | $9.99 |
| | Alligator Cables | 15 | $25.82 |
| | Perfboards | 6 | $7.29 |
| | Batteries, Chargers | 12, 2 | $151.35 |
| | Banana Cables, Arduino Cables | 1, 1 | $126.97 |
| Control System | TMP36 Sensors | 6 | $29.41 |
| | Arduino Micro | 3 | $67.80 |
| | MOSFET Heat sink | 4 | $6.32 |
| | Arduino Cables | 120 | $12.99 |
| | Buck Converter | 9 | $74.55 |
| | MOSFET | 3 | $14.37 |
| | Buck, Boost, Big Boost Converter | 3, 3, 3 | $108.03 |
| | Relays, Diodes | 3, 2 | $19.78 |
| | Relays | 3 | $8.16 |
| | Arduino Relay | 1 | $12.78 |
| Miscellaneous | Dell i5547-5780sLV Notebook | 1 | $650.33 |
| | Presentation Board | 1 | $10.10 |
| | Double-sided Tape | 2 | $4.35 |
| | **TOTAL** | | **$3,041.92** |
| | **REMAINING** | | **$58.08** |

## *B.2 Gantt Chart*

Shown in the following pages are two sections of our Gantt chart. The first Gantt chart includes the schedule for the Fall and Winter quarters. The second Gantt chart includes the schedule for the Spring quarter.

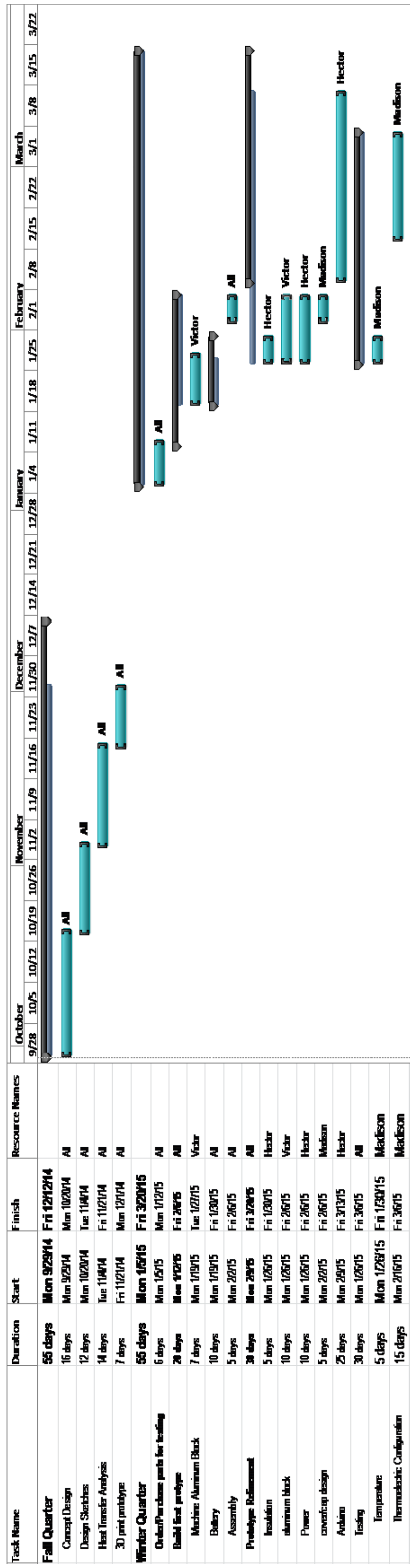


***Figure B.1:*** Fall and Winter quarter Gantt chart.

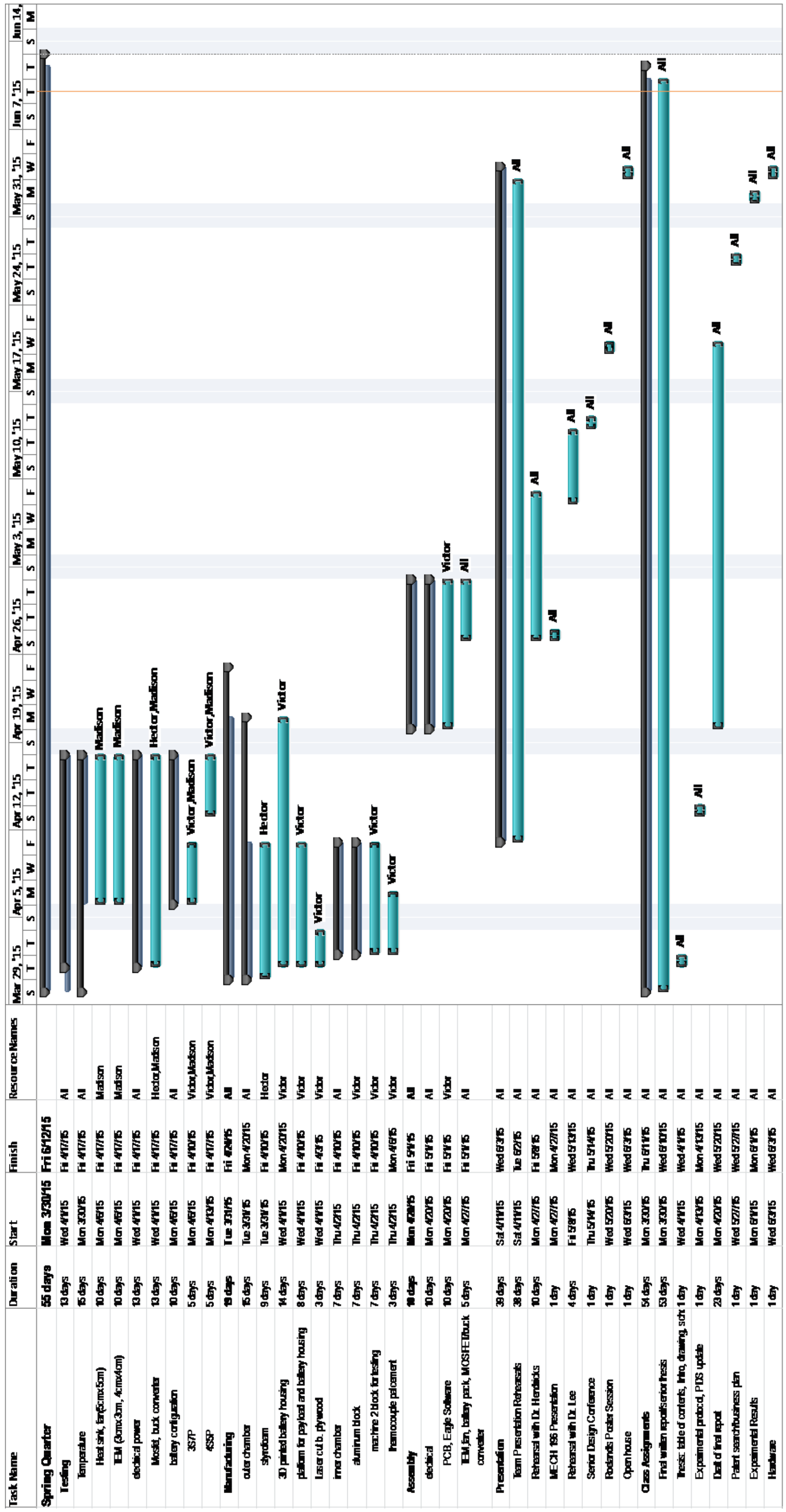
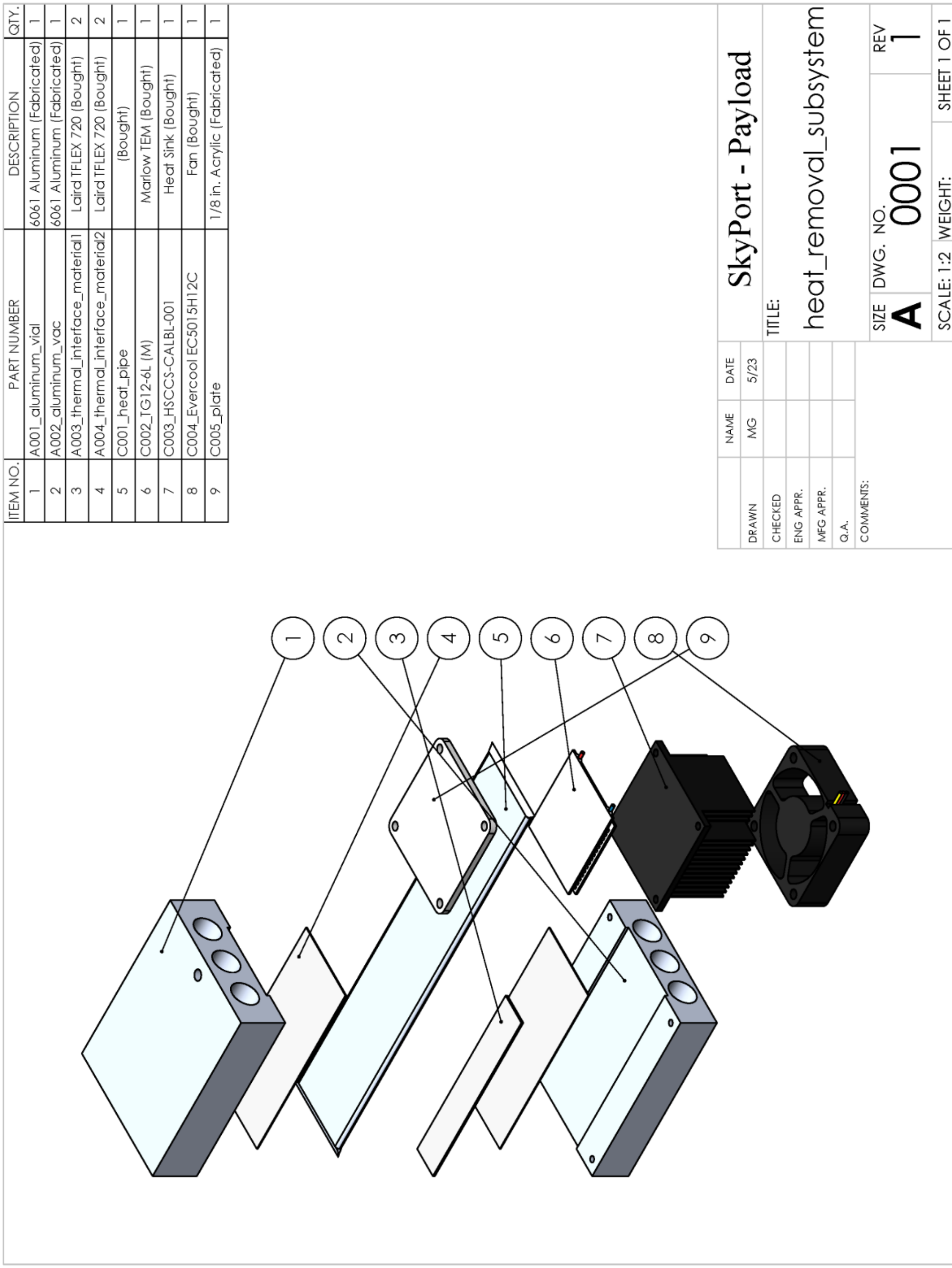


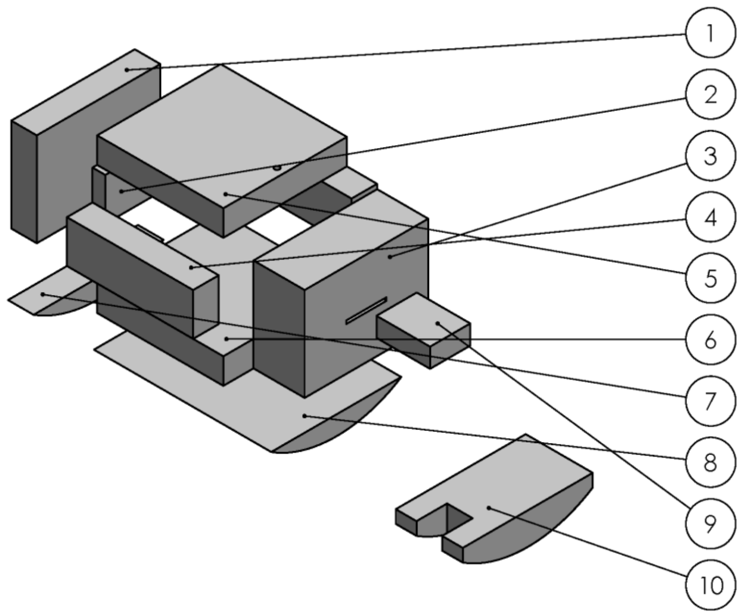

***Figure B.2:*** Spring quarter Gantt chart.

# Appendix C – Design Drawings




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | A001_aluminum_vial | 6061 Aluminum (Fabricated) | 1 |
| 2 | A002_aluminum_vac | 6061 Aluminum (Fabricated) | 1 |
| 3 | A003_thermal_interface_material1 | Laird TFLEX 720 (Bought) | 2 |
| 4 | A004_thermal_interface_material2 | Laird TFLEX 720 (Bought) | 2 |
| 5 | C001_heat_pipe | (Bought) | 1 |
| 6 | C002_TG12-6L (M) | Marlow TEM (Bought) | 1 |
| 7 | C003_HSCCS-CALBL-001 | Heat Sink (Bought) | 1 |
| 8 | C004_Evercool EC5015H12C | Fan (Bought) | 1 |
| 9 | C005_plate | 1/8 in. Acrylic (Fabricated) | 1 |

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | B001_insulation_back | EPS Foam (Fabricated) | 1 |
| 2 | B002_insulation_seal | EPS Foam (Fabricated) | 1 |
| 3 | B003_insulation_front | EPS Foam (Fabricated) | 1 |
| 4 | B004_insulation_sides | EPS Foam (Fabricated) | 2 |
| 5 | B005_insulation_top | EPS Foam (Fabricated) | 1 |
| 6 | B006_insulation_bottom | EPS Foam (Fabricated) | 1 |
| 7 | B007_insulation_cap_curve | EPS Foam (Fabricated) | 1 |
| 8 | B008_insulation_body_curve | EPS Foam (Fabricated) | 1 |
| 9 | B009_insulation_heat_pipe | EPS Foam (Fabricated) | 1 |
| 10 | B010_insulation_battery_curve | EPS Foam (Fabricated) | 1 |




| | NAME | DATE |
|---|---|---|
| DRAWN | MG | 5/23 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |
| COMMENTS: | | |

SkyPort - Payload

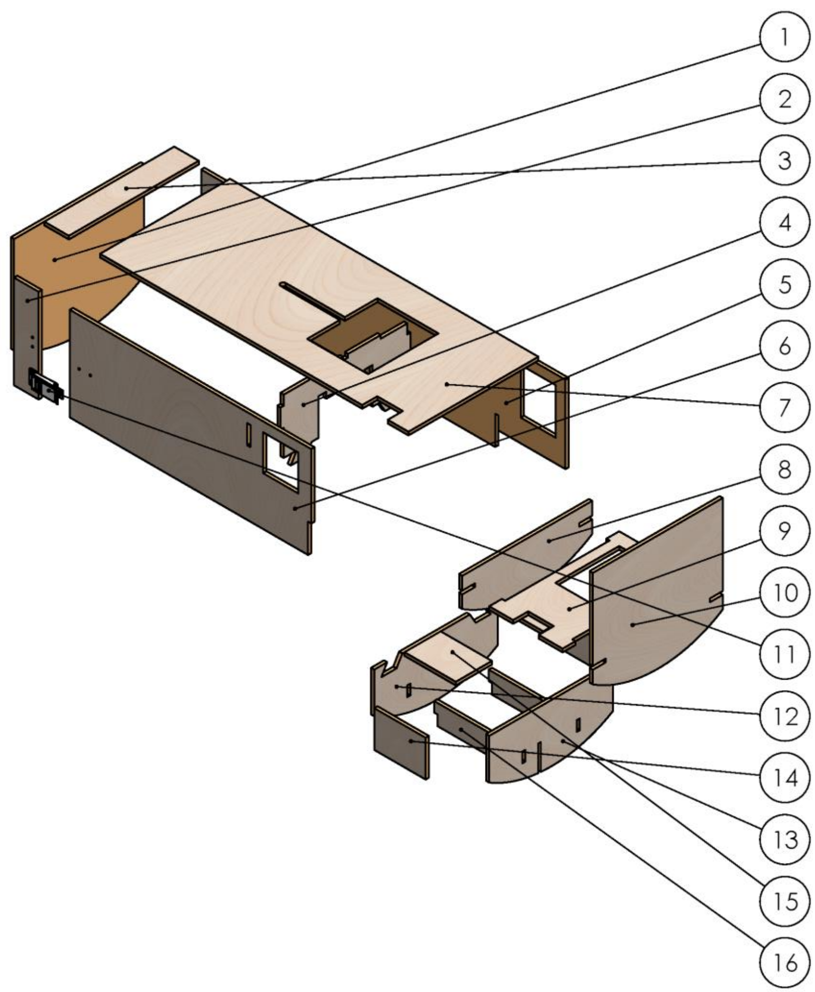
TITLE:

outer_insulation_subsystem

SIZE A | DWG. NO. 0002 | REV 1

SCALE: 1:4 | WEIGHT: | SHEET 1 OF 2

5 4 3 2 1




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | B011_shell_cap_back | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 2 | B012_shell_cap_sides | 1/8 in. Birch Plywood (Fabricated) | 2 |
| 3 | B013_shell_cap_top | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 4 | B014_shell_front | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 5 | B015_shell_side_left | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 6 | B016_shell_side_right | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 7 | B017_shell_top | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 8 | B018_battery_mount_back | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 9 | B019_battery_mount_bottom | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 10 | B020_battery_mount_front | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 11 | B021_latch | Spring Draw Latch (Bought) | 2 |
| 12 | C006_ventilation_back_plate | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 13 | C007_ventilation_front_plate | 1/8 in. Birch Plywood (Fabricated) | 1 |
| 14 | C008_ventilation_side_plate | 1/8 in. Birch Plywood (Fabricated) | 2 |
| 15 | C009_ventilation_top_plate | 1/8 in. Birch Plywood (Fabricated) | 2 |
| 16 | C010_ventilation_divider | 1/8 in. Birch Plywood (Fabricated) | 2 |

| | NAME | DATE |
|---|---|---|
| DRAWN | MG | 5/23 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |
| COMMENTS: | | |

SkyPort - Payload

TITLE:

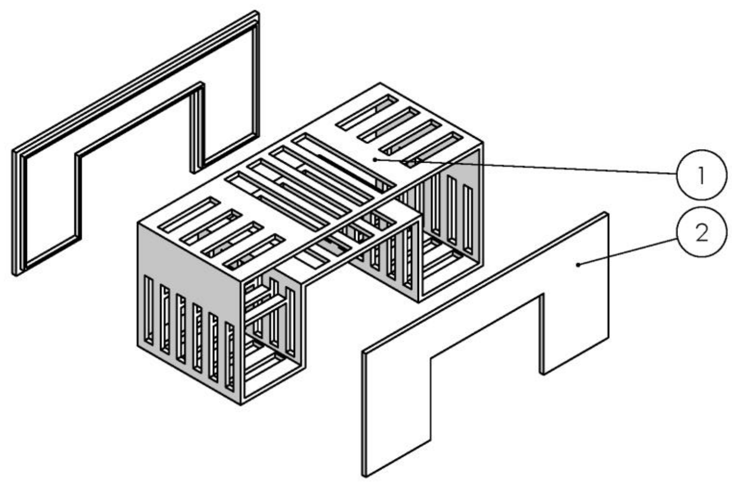
outer_insulation_subsystem

SIZE A | DWG. NO. 0002 | REV 1

SCALE: 1:4 | WEIGHT: | SHEET 2 OF 2

5 4 3 2 1

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | E001_electronic_housing | ABS Plastic (Fabricated) | 1 |
| 2 | E002_electronic_lid | ABS Plastic (Fabricated) | 2 |




| | NAME | DATE |
|---|---|---|
| DRAWN | MG | 5/23 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |
| COMMENTS: | | |

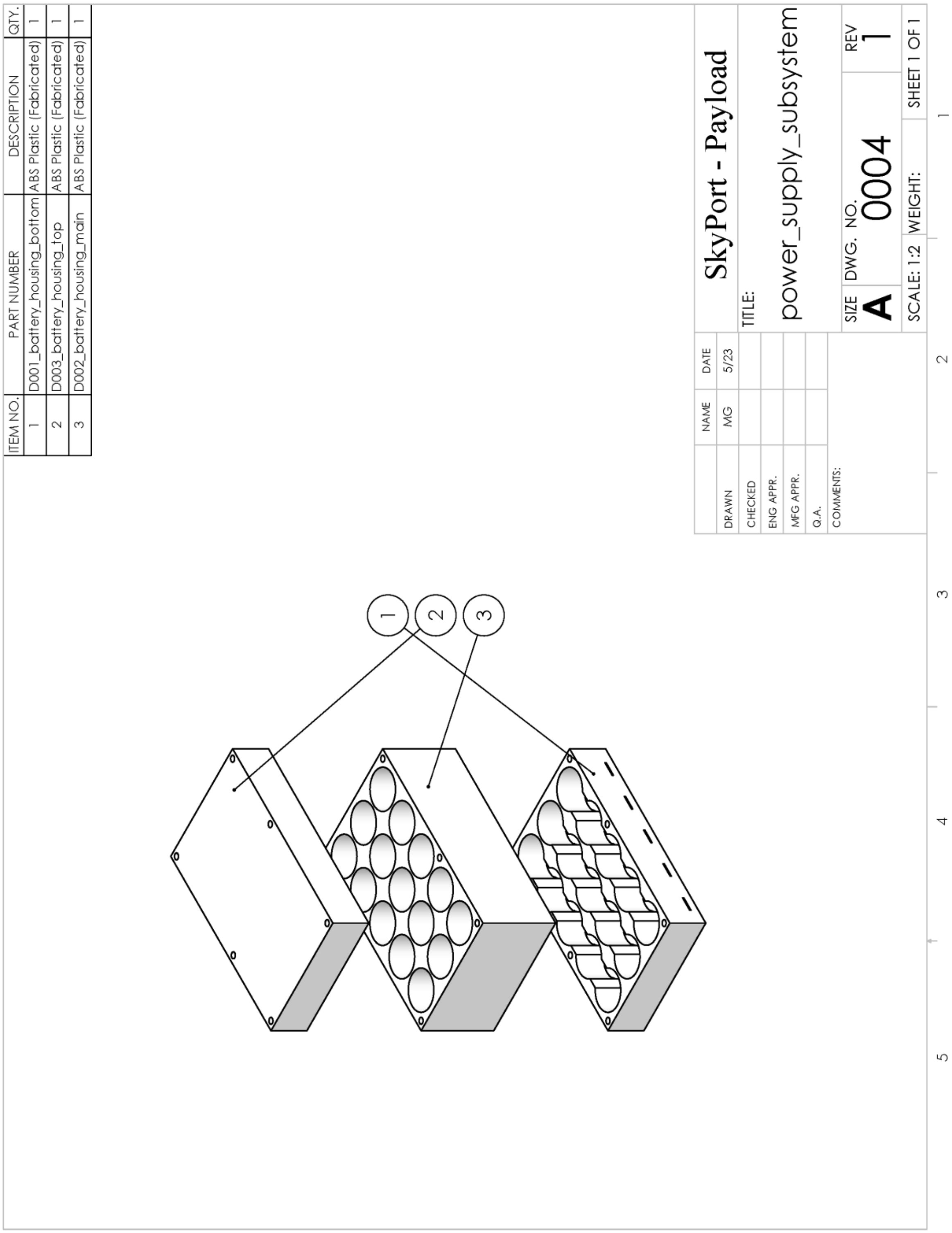
SkyPort - Payload

TITLE:

temperature_control_subsystem

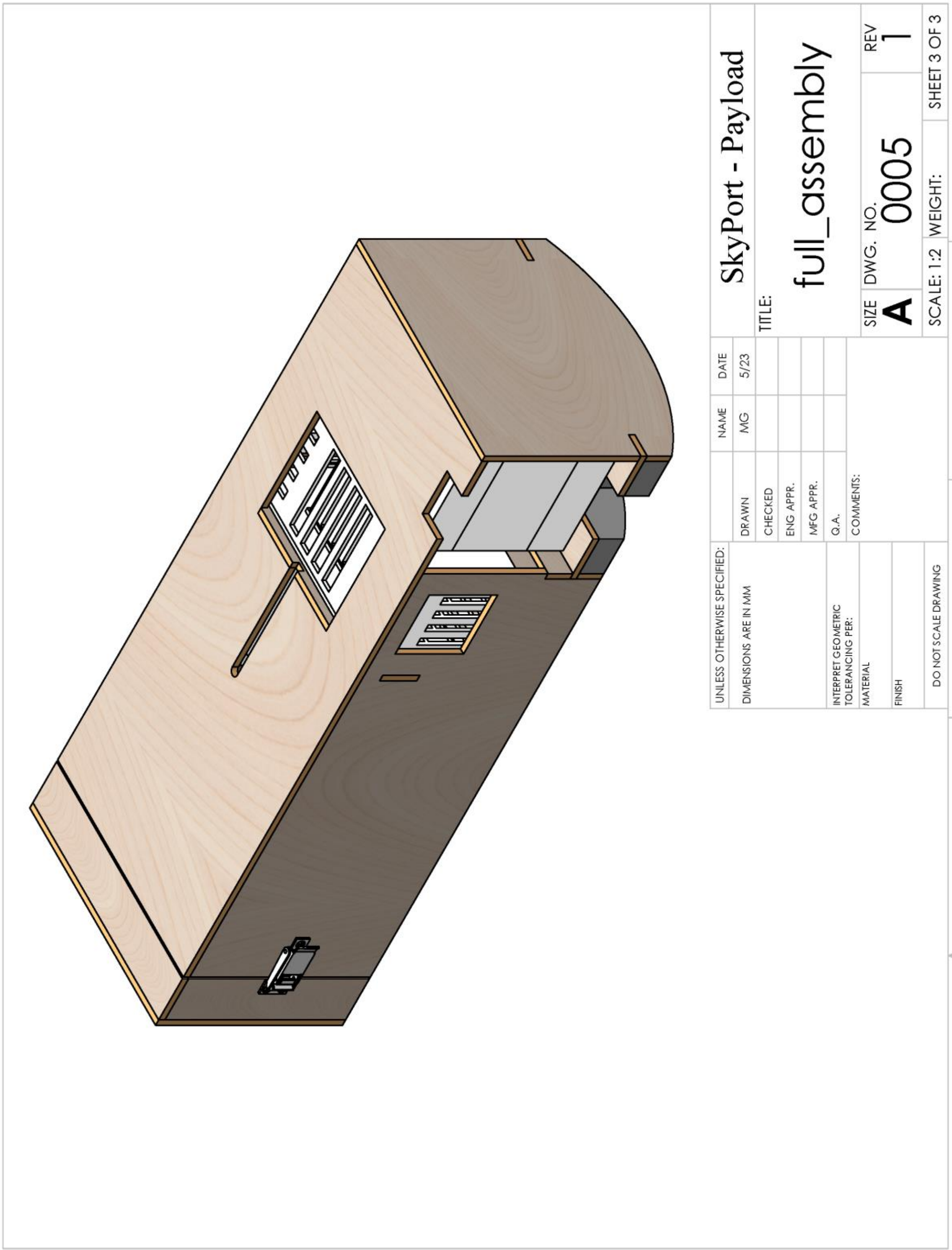
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | 0003 | 1 |
| SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1 |

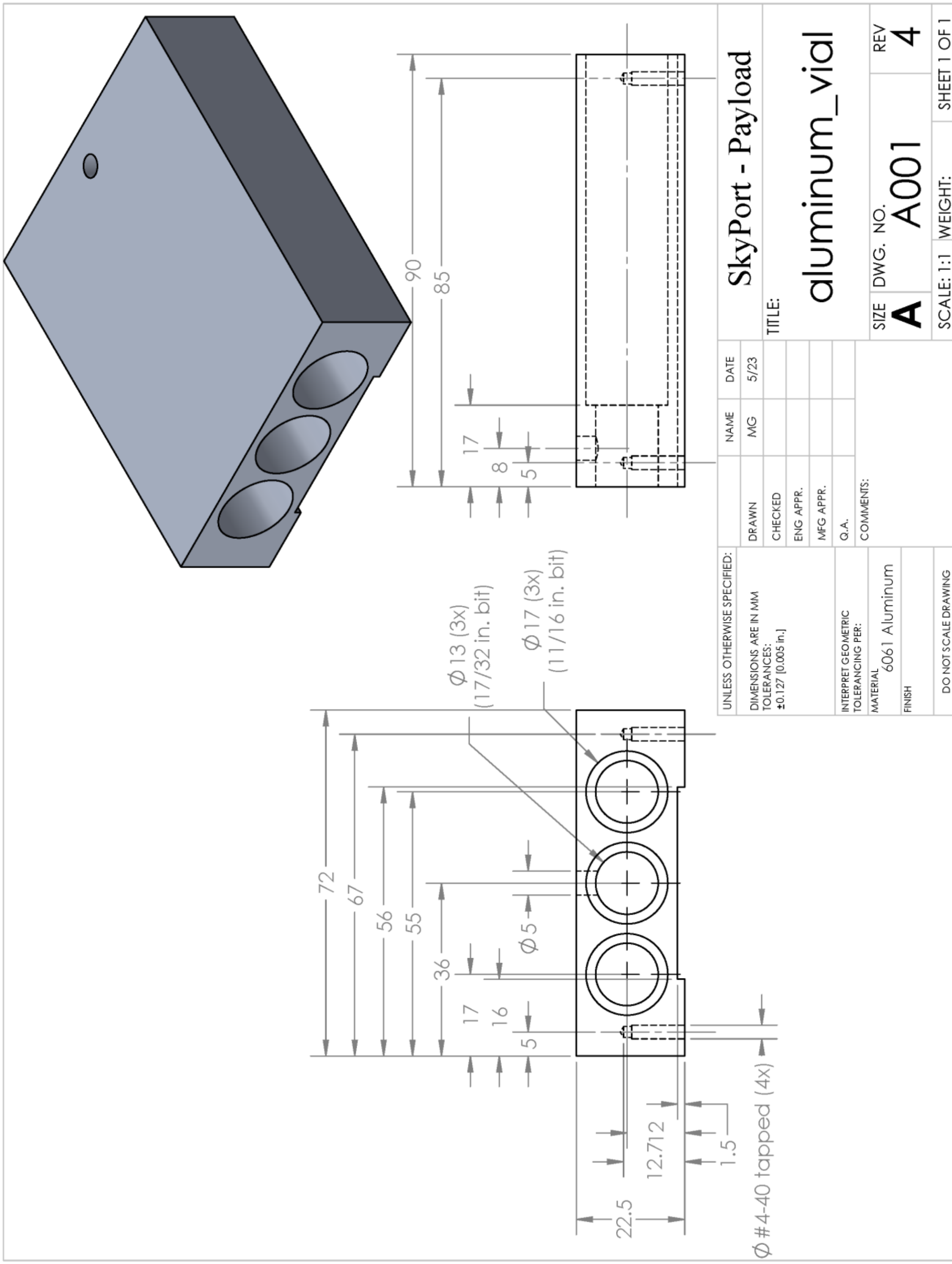
5 4 3 2 1

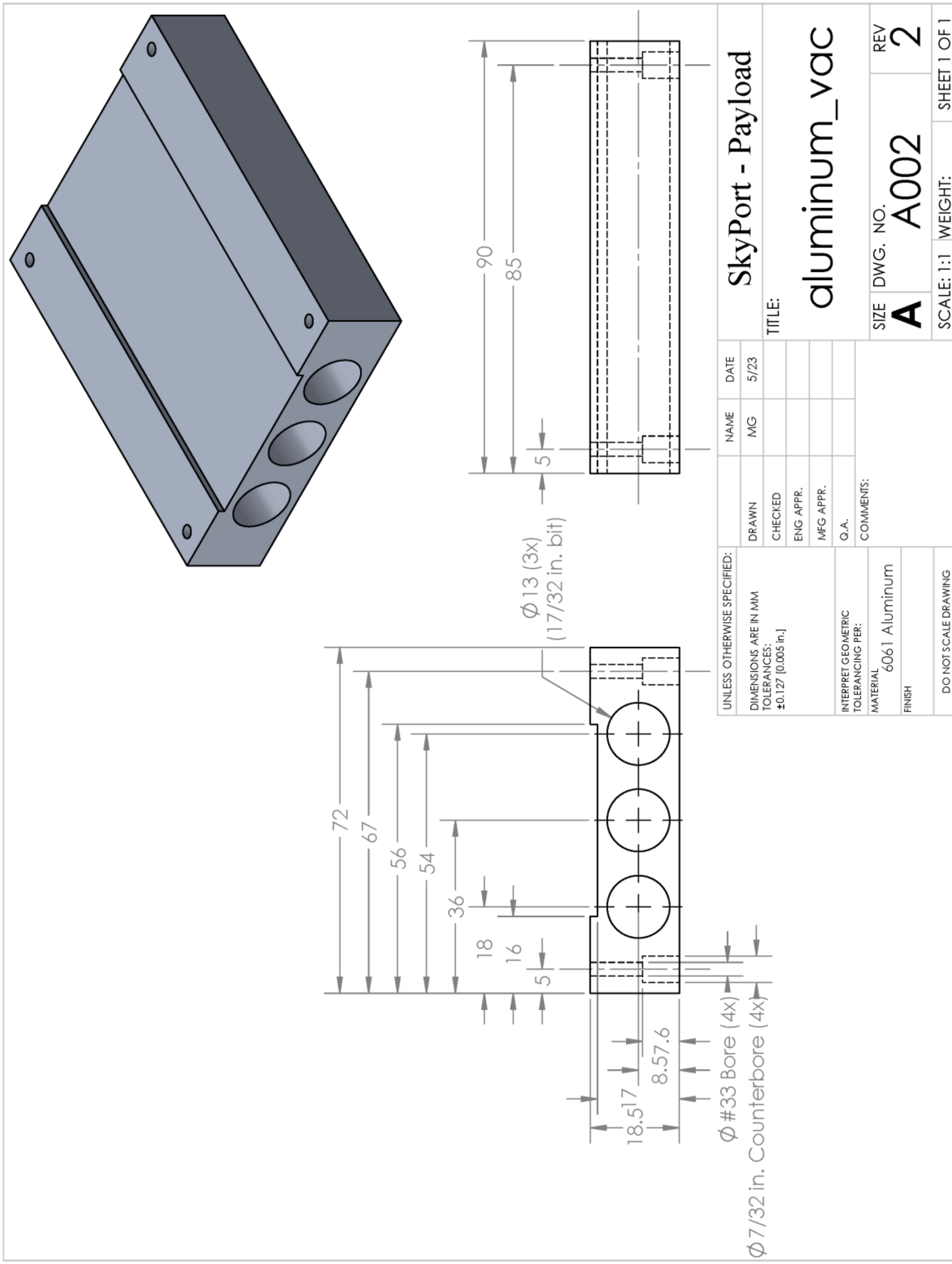

ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | D001_battery_housing_bottom | ABS Plastic (Fabricated) | 1
2 | D003_battery_housing_top | ABS Plastic (Fabricated) | 1
3 | D002_battery_housing_main | ABS Plastic (Fabricated) | 1
1
2
3
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
power_supply_subsystem
SIZE
A
DWG. NO.
0004
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


338.250
114.831
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
full_assembly
SIZE
A
DWG. NO.
0005
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 3
1
2
3
4
5

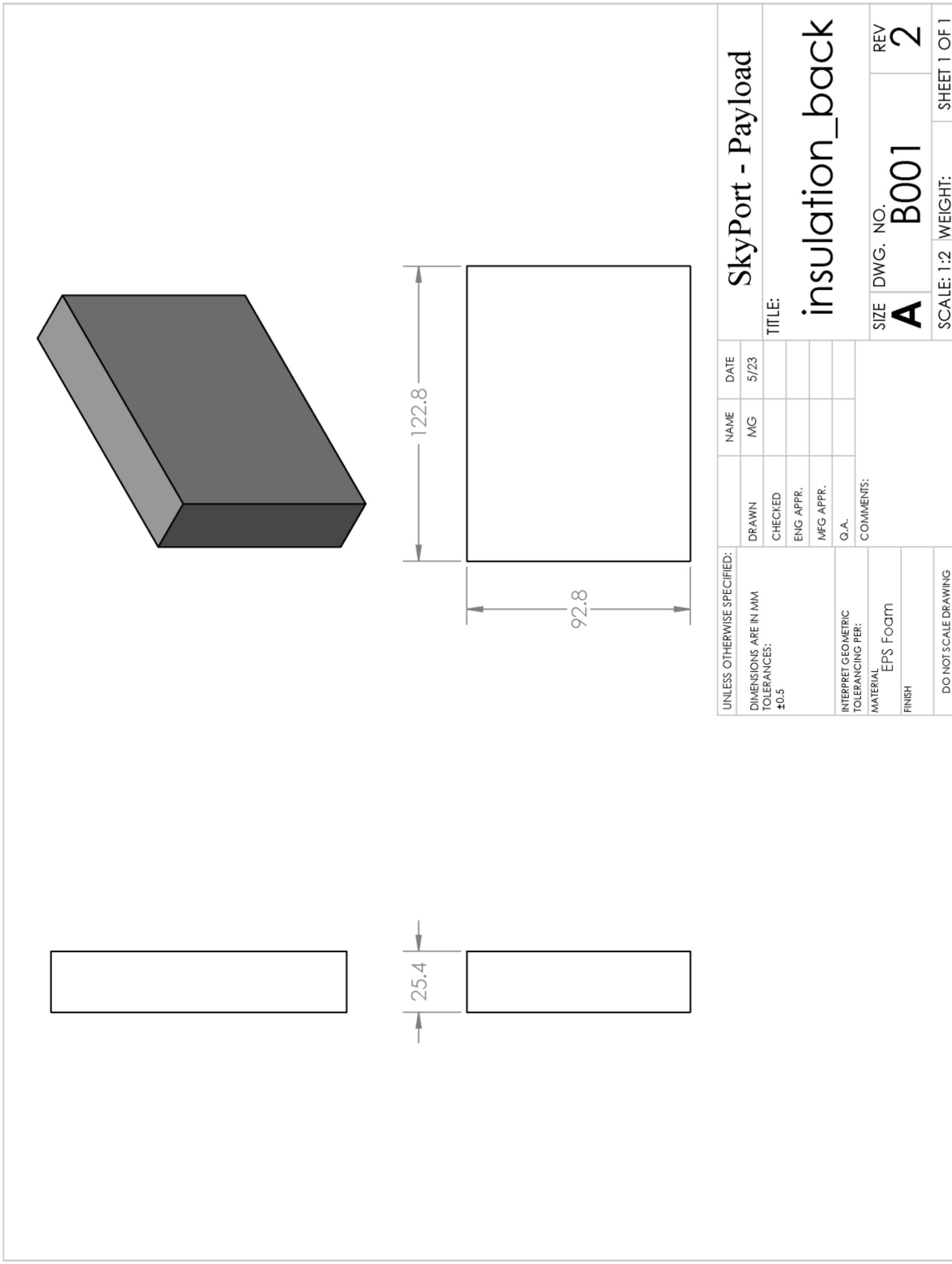

145.380
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
full_assembly
SIZE
A
DWG. NO.
0005
REV
1
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
1
2
3
4
5

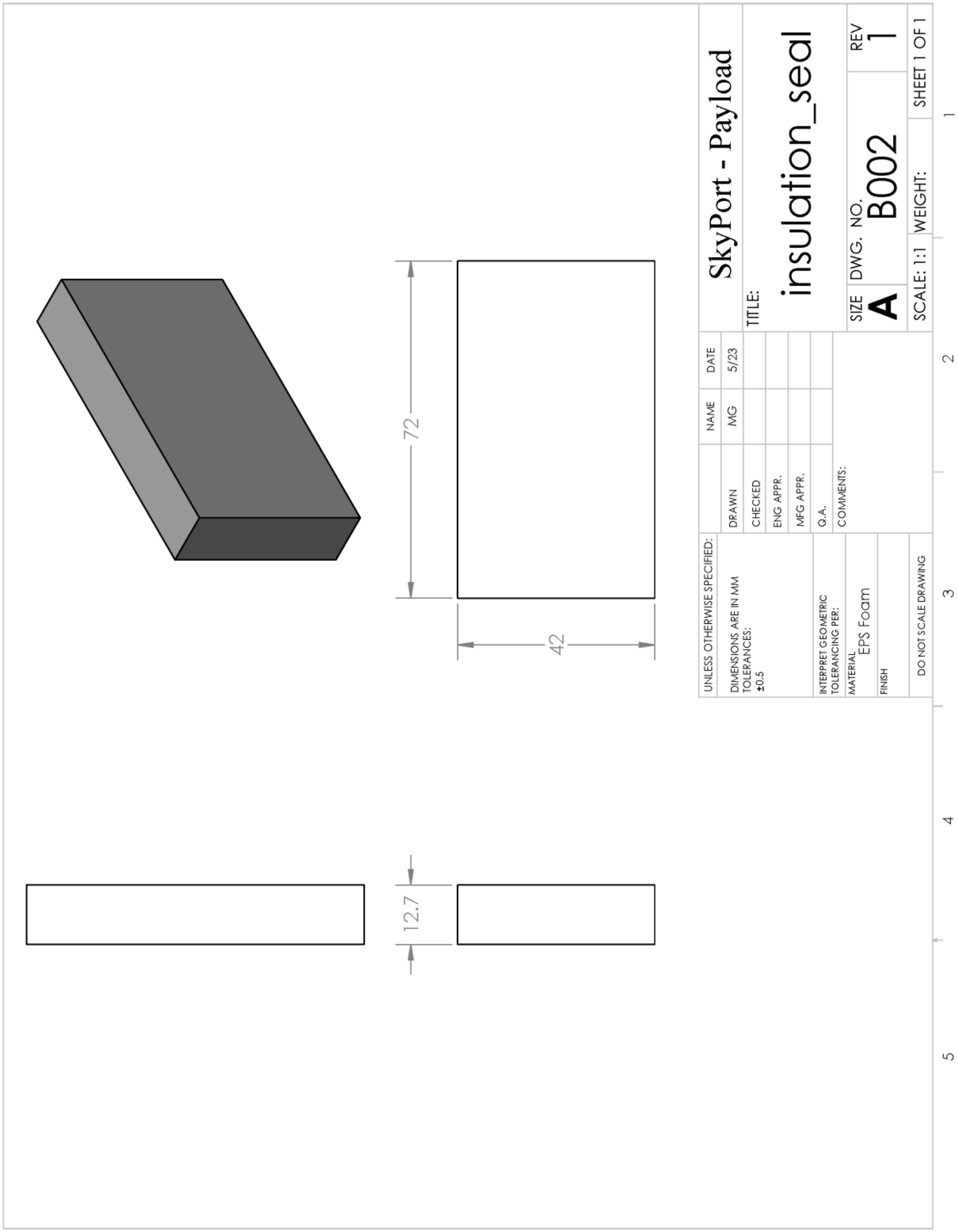

SkyPort - Payload
TITLE:
full_assembly
SIZE
A
DWG. NO.
0005
REV
1
SCALE: 1:2
WEIGHT:
SHEET 3 OF 3
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
1
2
3
4
5


SkyPort - Payload
TITLE:
aluminum_vial
SIZE A
DWG. NO. A001
REV 4
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.127 [0.005 in.]
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN MG 5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Ø 13 (3x)
(17/32 in. bit)
Ø 17 (3x)
(11/16 in. bit)
Ø 5
Ø #4-40 tapped (4x)
72
67
56
55
36
17
16
5
22.5
12.712
1.5
90
85
17
8
5

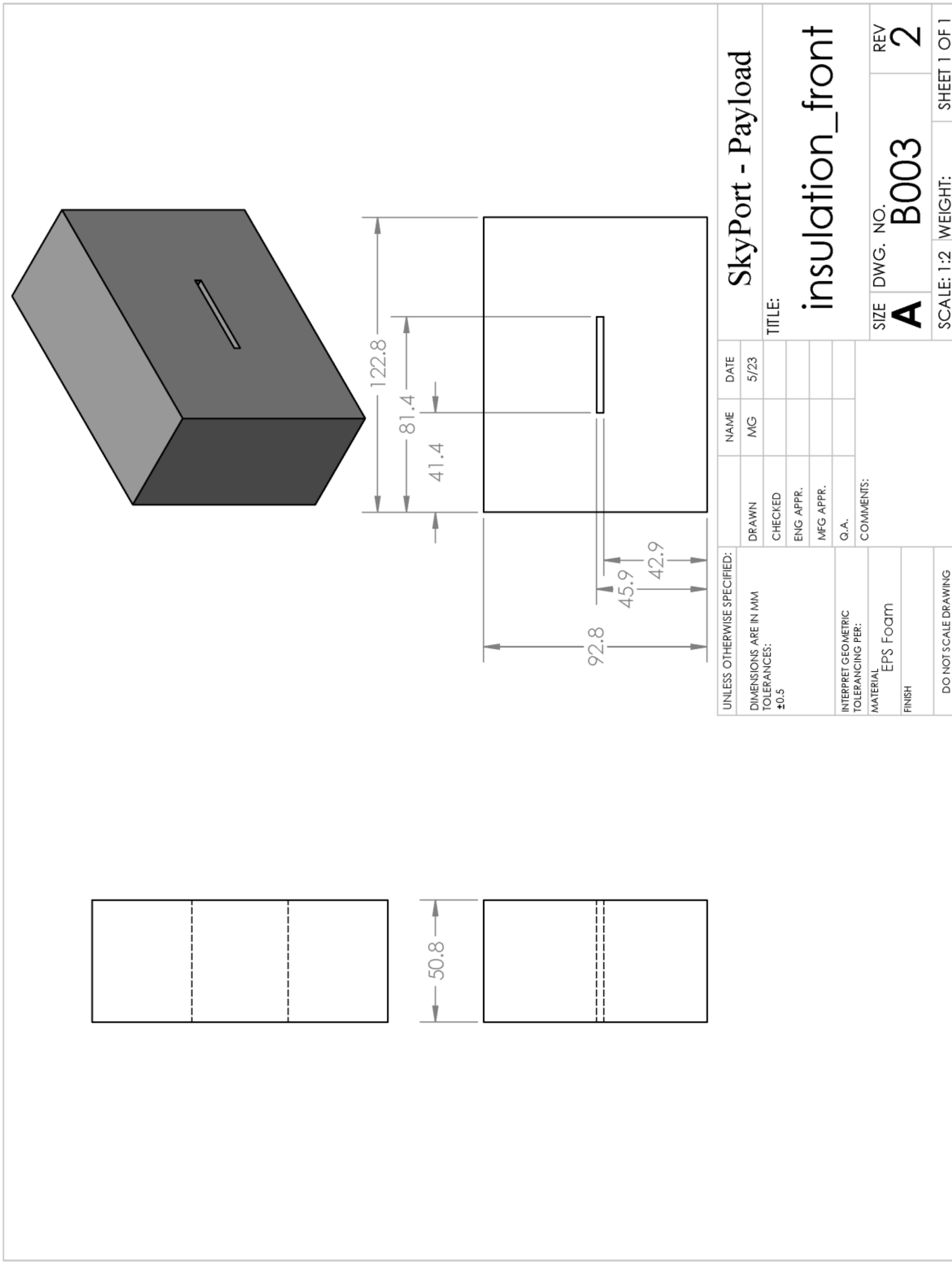


SkyPort - Payload
TITLE:
aluminum_vac
SIZE
A
DWG. NO.
A002
REV
2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.127 [0.005 in.]
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Ø13 (3x)
(17/32 in. bit)
Ø #33 Bore (4x)
Ø7/32 in. Counterbore (4x)
90
85
5
72
67
56
54
36
18
16
5
18.5
17
8.5
7.6
1
2
3
4
5

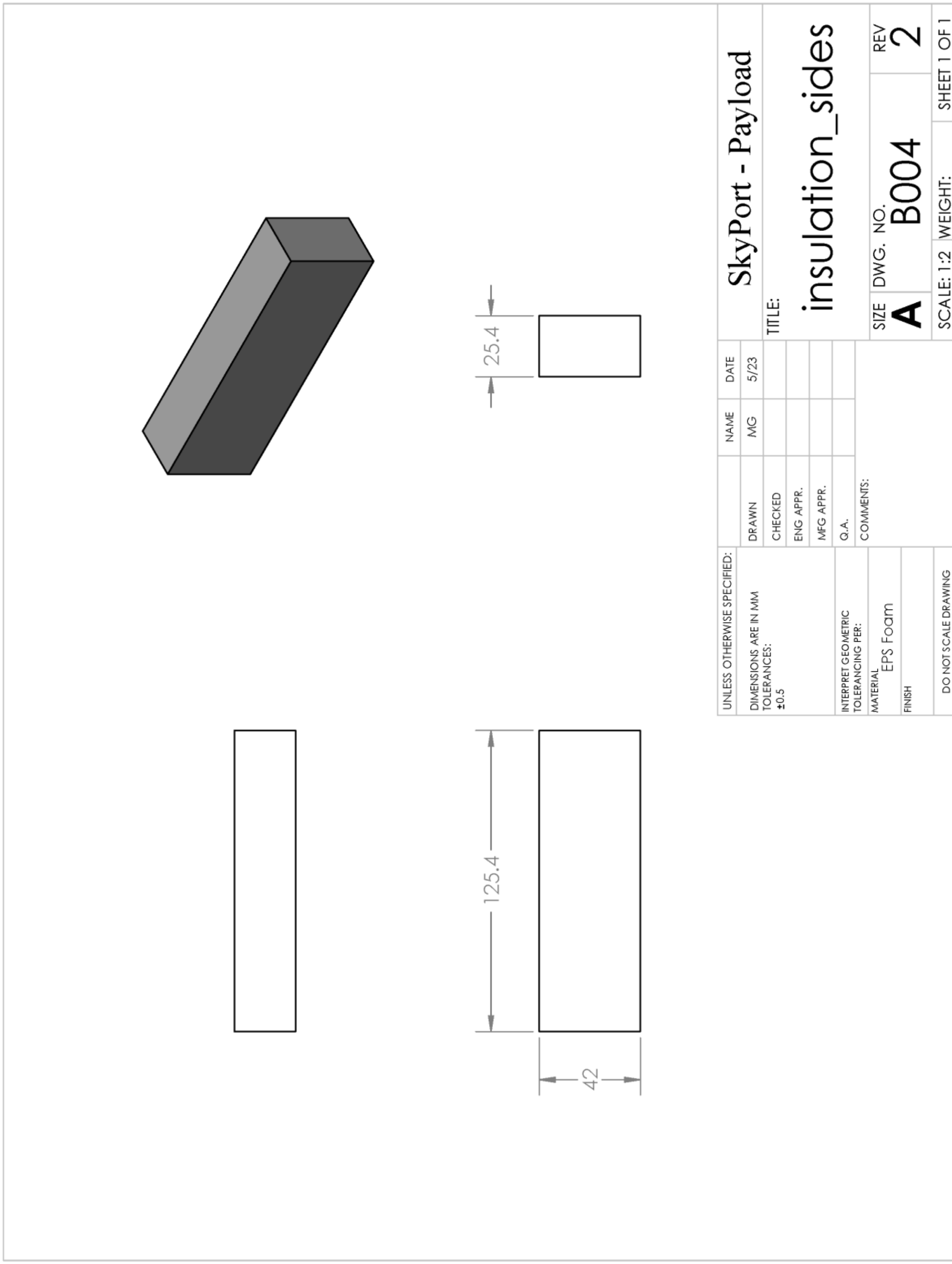

122.8
92.8
25.4
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
insulation_back
SIZE
A
DWG. NO.
B001
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

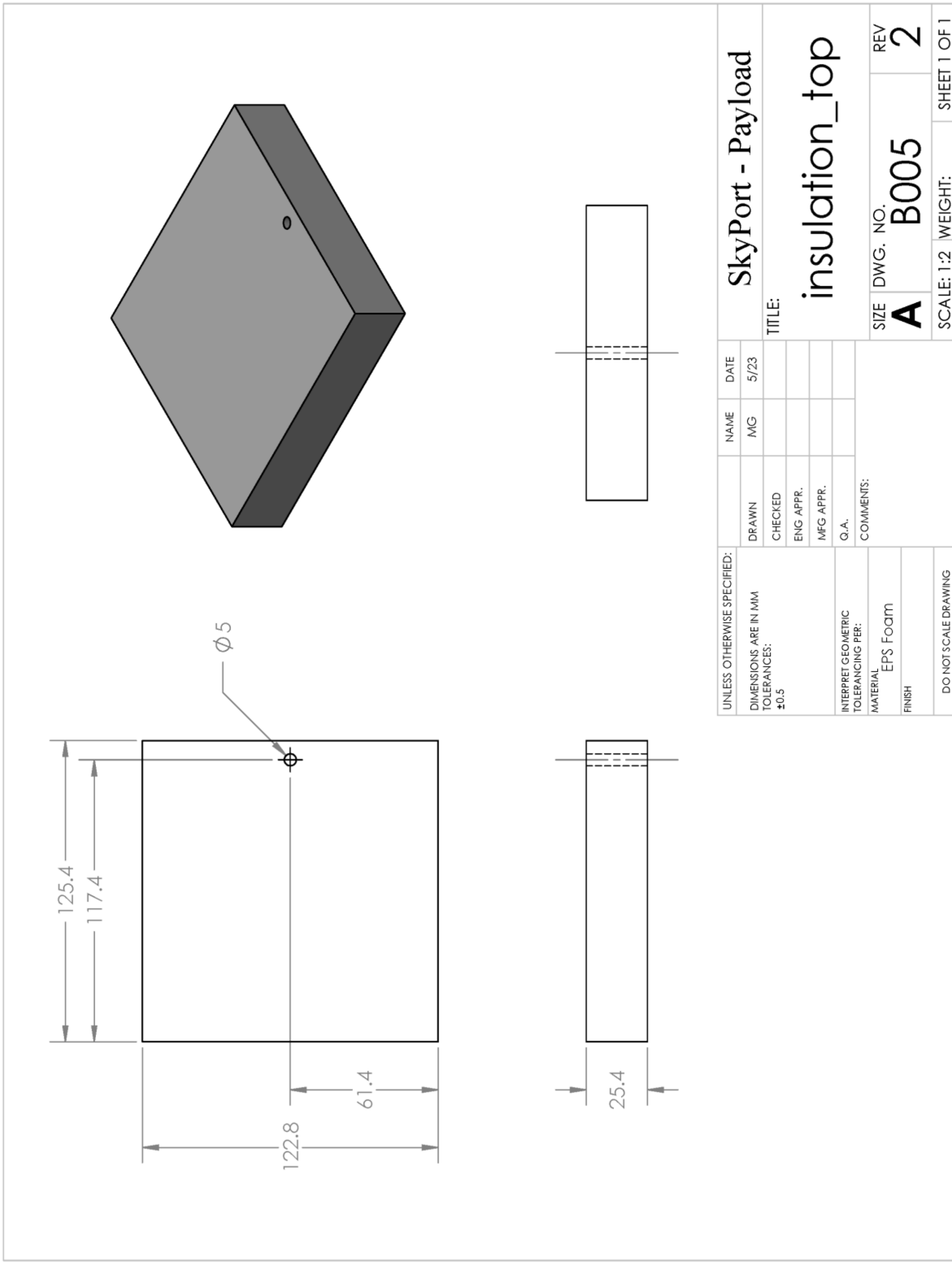


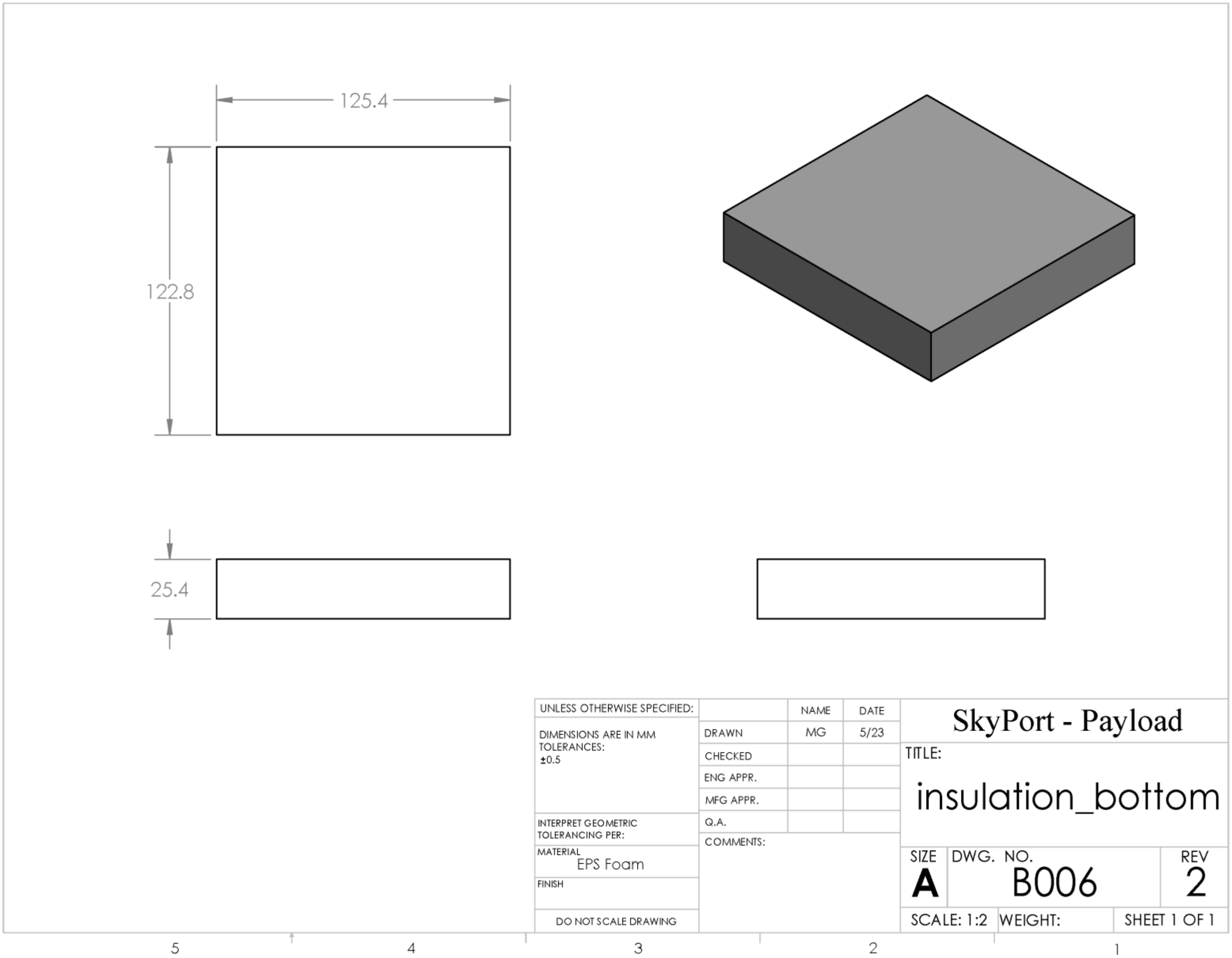
SkyPort - Payload
TITLE:
insulation_seal
SIZE
A
DWG. NO.
B002
REV
1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
72
42
12.7
1
2
3
4
5



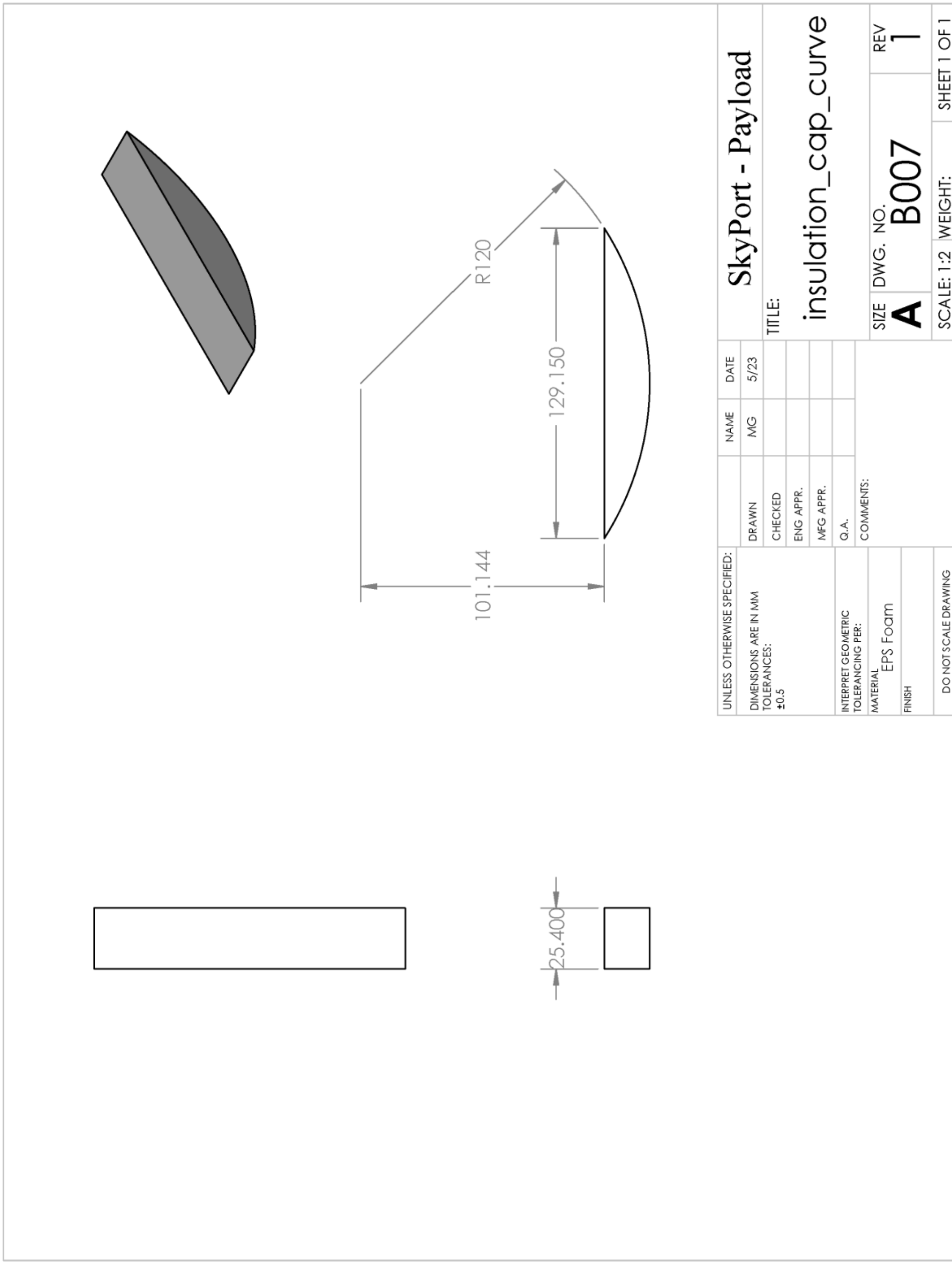
SkyPort - Payload
TITLE:
insulation_front
SIZE A
DWG. NO. B003
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN MG 5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
122.8
81.4
41.4
92.8
45.9
42.9
50.8


25.4
125.4
42
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
insulation_sides
SIZE
A
DWG. NO.
B004
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

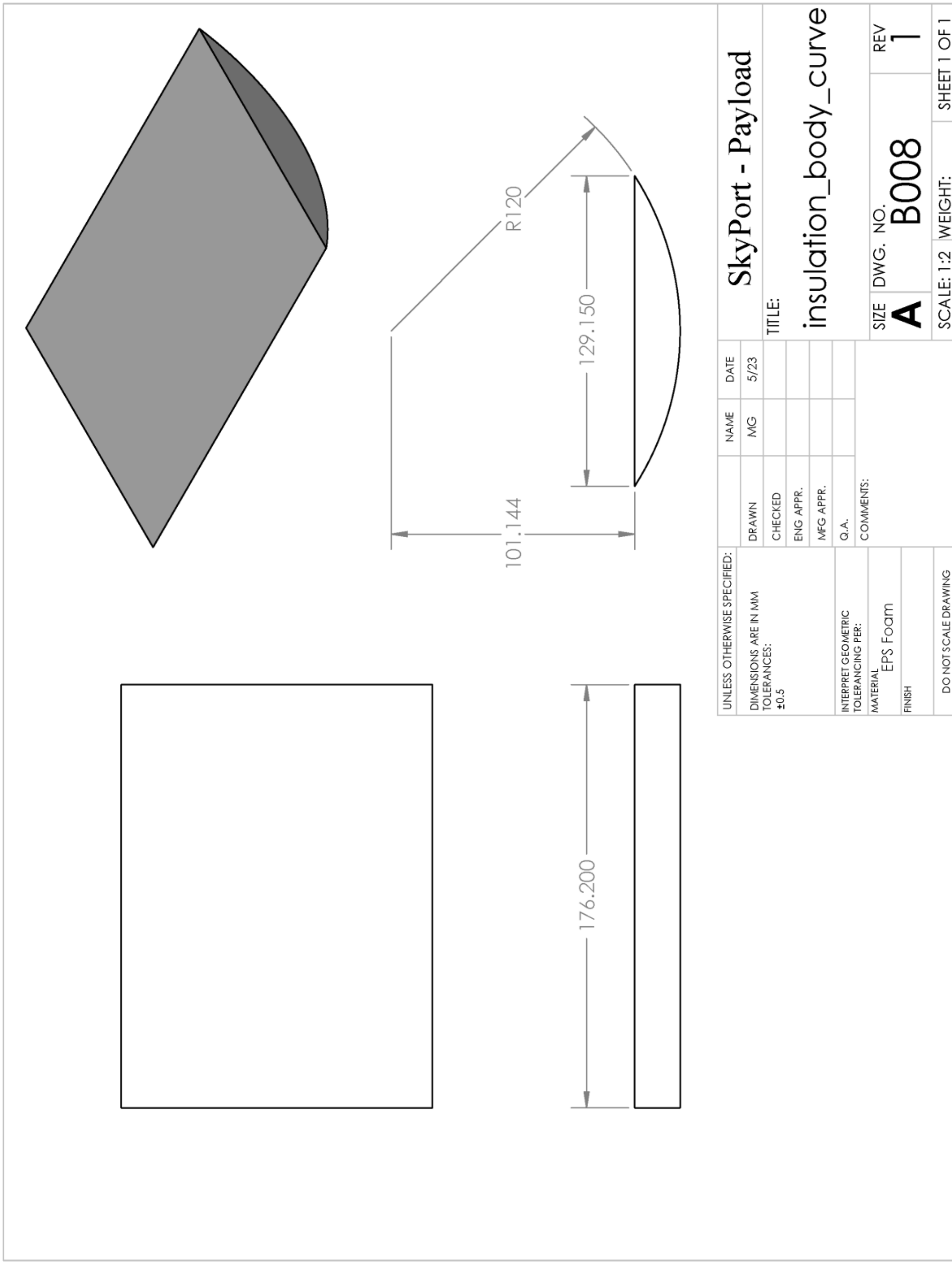

SkyPort - Payload
TITLE:
insulation_top
SIZE A
DWG. NO. B005
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Ø 5
125.4
117.4
122.8
61.4
25.4
1
2
3
4
5

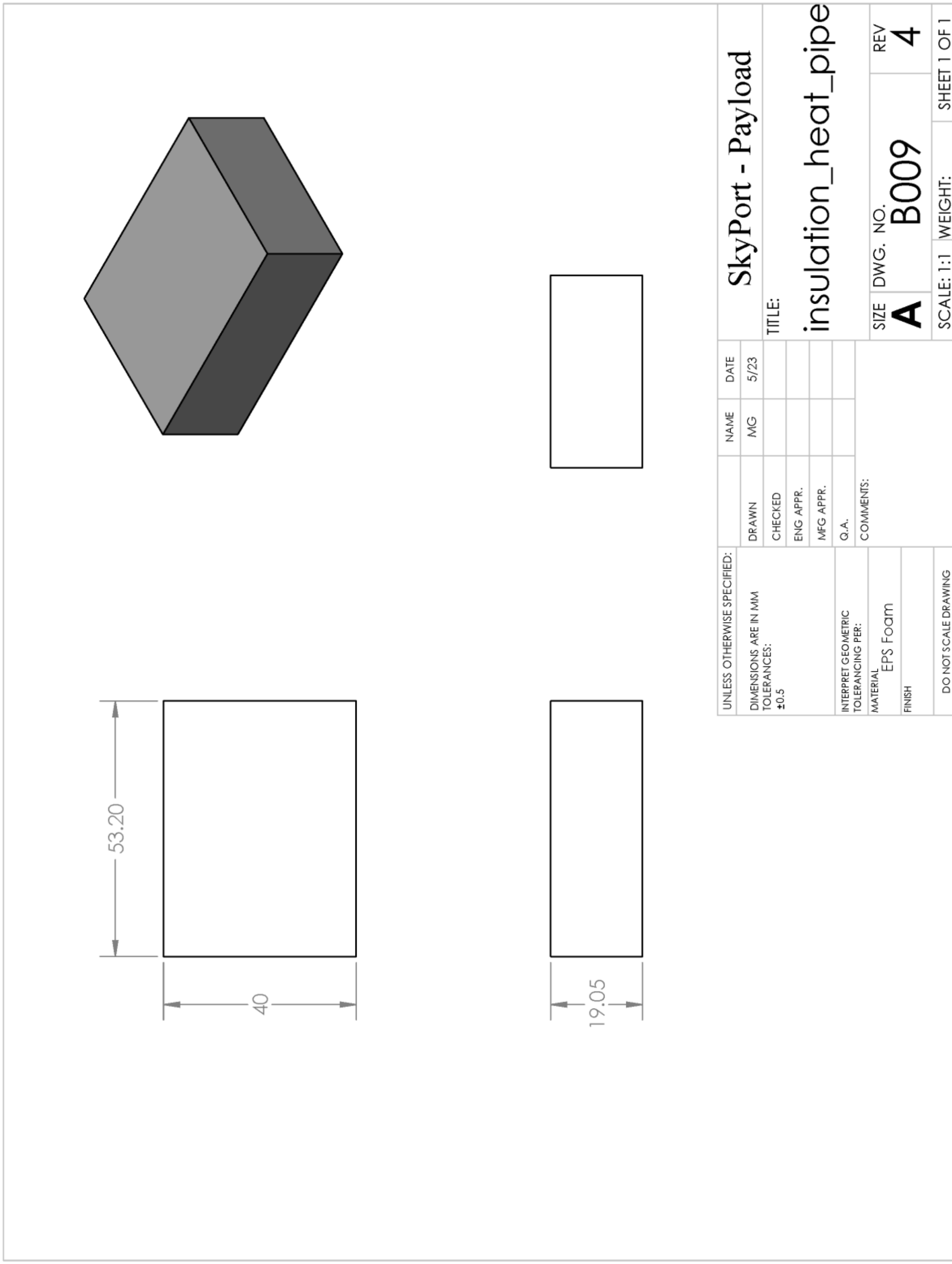


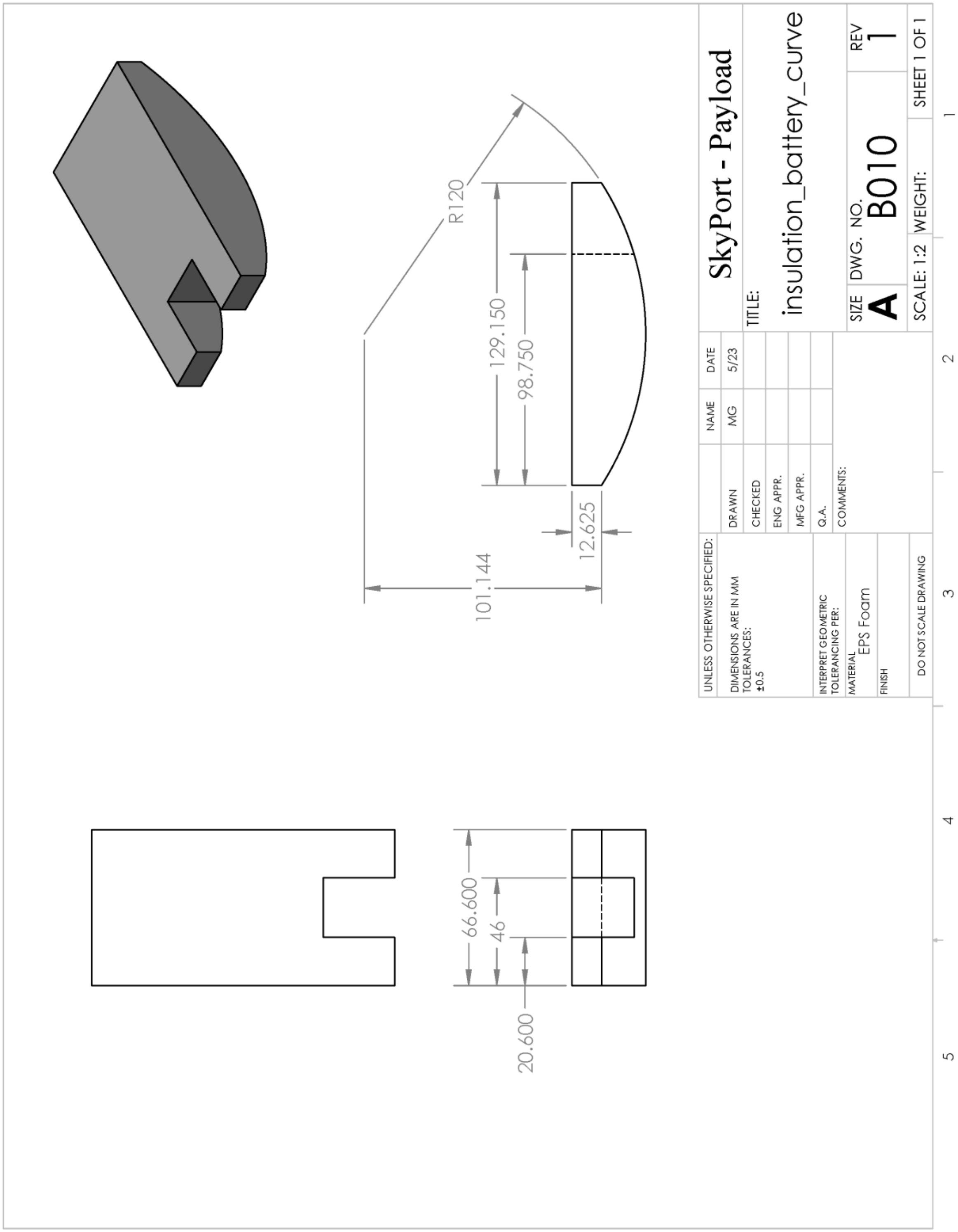
125.4
122.8
25.4
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
insulation_bottom
SIZE
A
DWG. NO.
B006
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



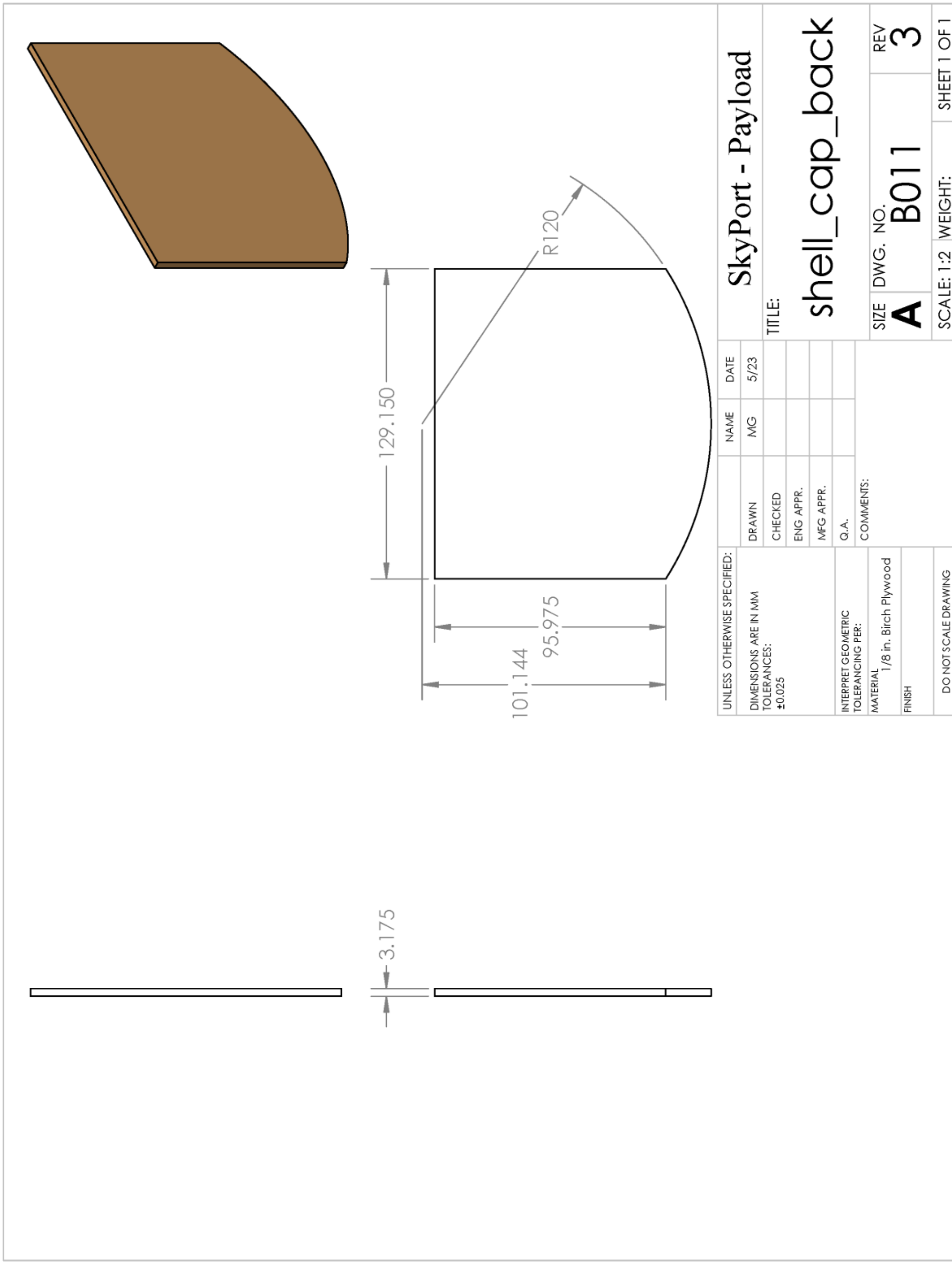
SkyPort - Payload
TITLE:
insulation_cap_curve
SIZE A
DWG. NO. B007
REV 1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R120
129.150
101.144
25.400

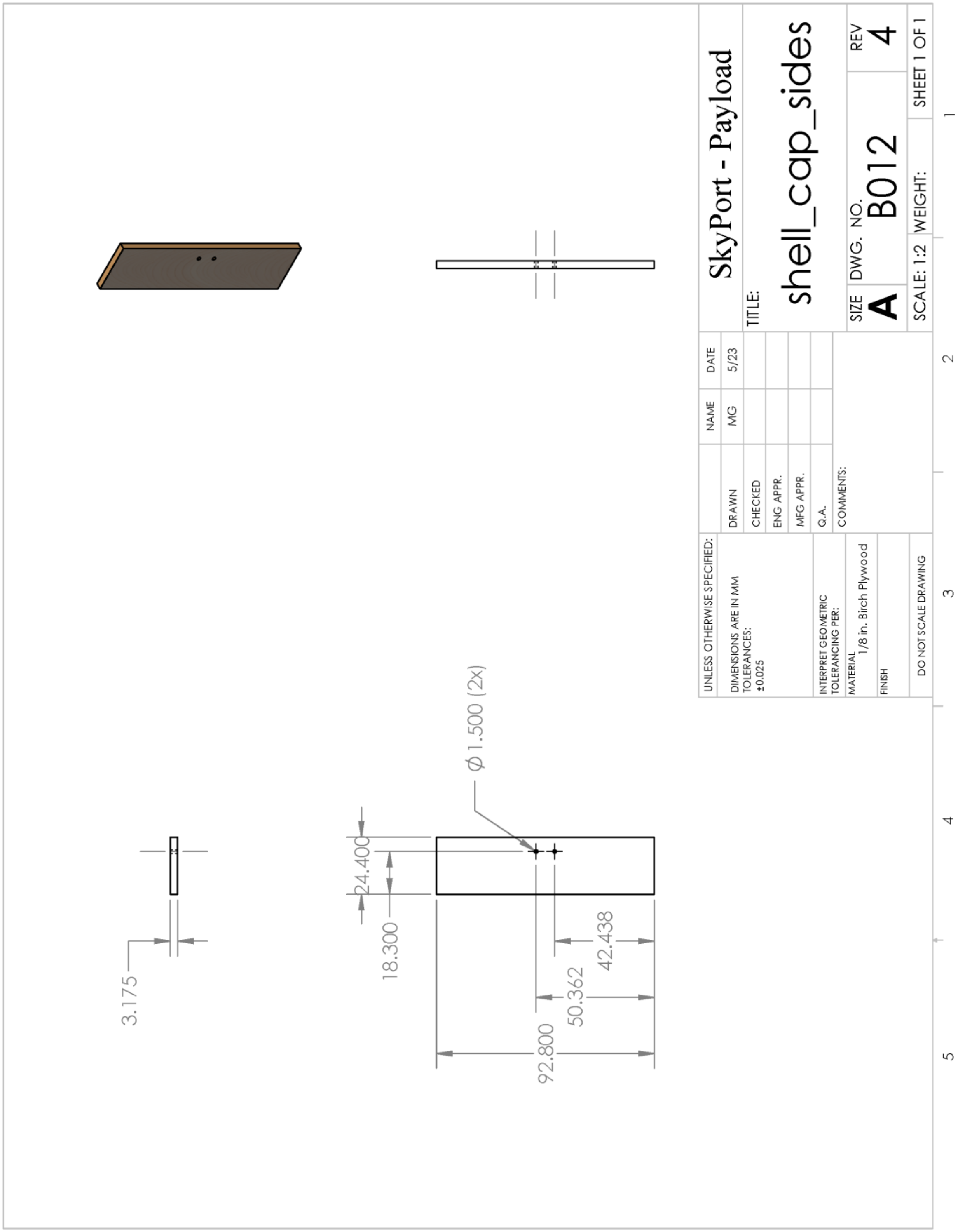

R120
129.150
101.144
176.200
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
insulation_body_curve
SIZE
A
DWG. NO.
B008
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5


53.20
40
19.05
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
insulation_heat_pipe
SIZE
A
DWG. NO.
B009
REV
4
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

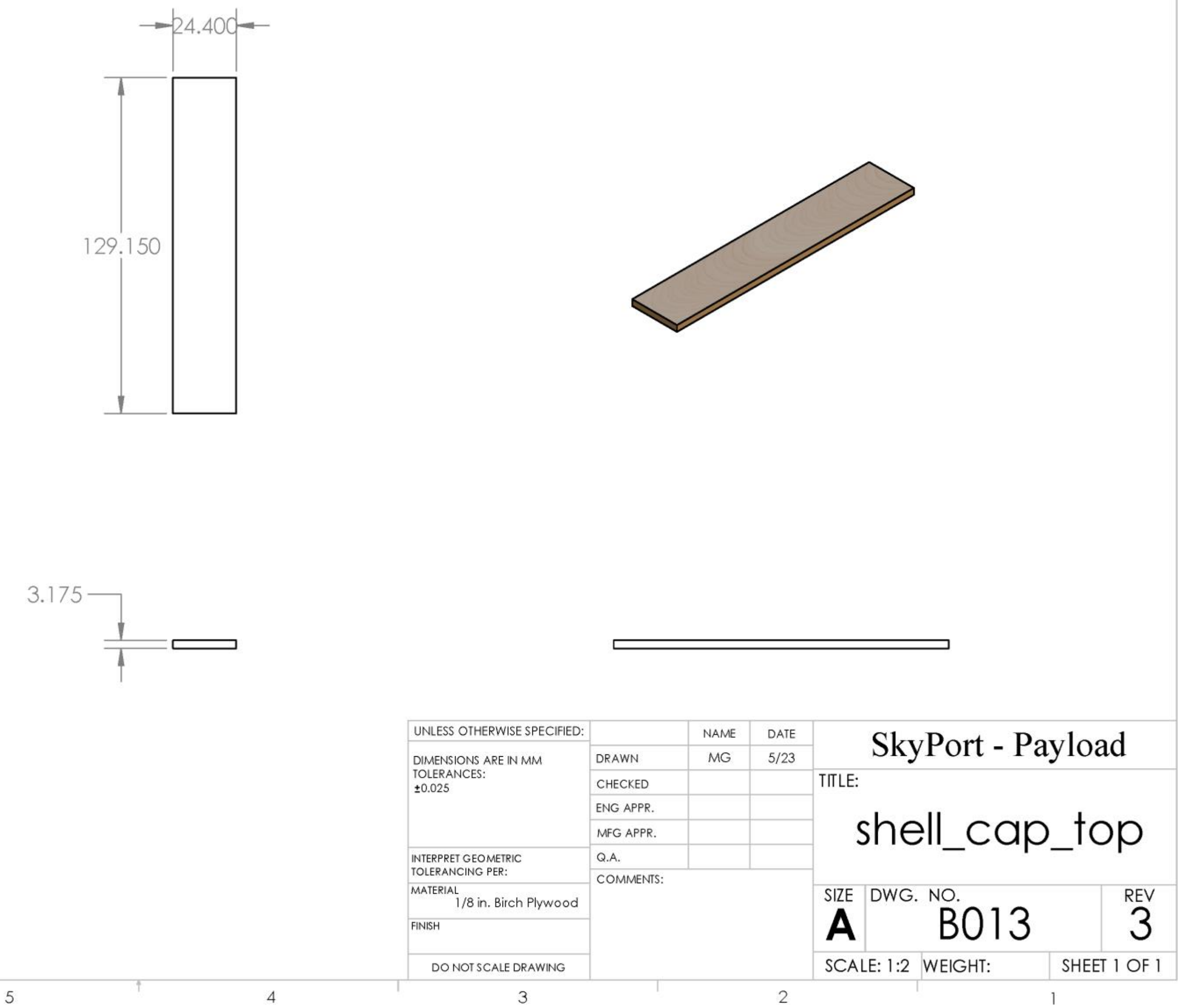


R120
129.150
98.750
12.625
101.144
66.600
46
20.600
SkyPort - Payload
TITLE:
insulation_battery_curve
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.5
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
EPS Foam
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SIZE
A
DWG. NO.
B010
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

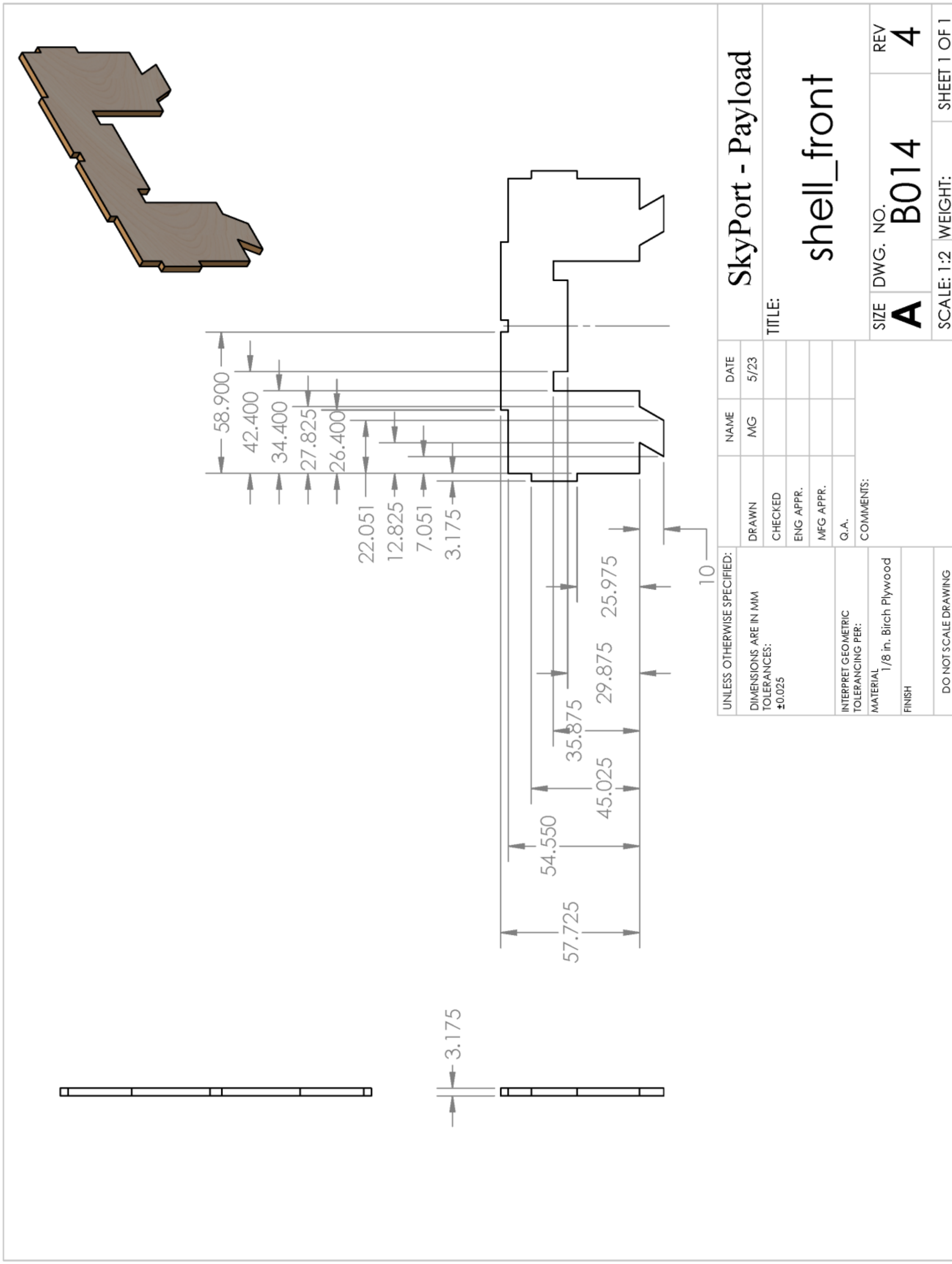

129.150
R120
95.975
101.144
3.175
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
shell_cap_back
SIZE
A
DWG. NO.
B011
REV
3
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5

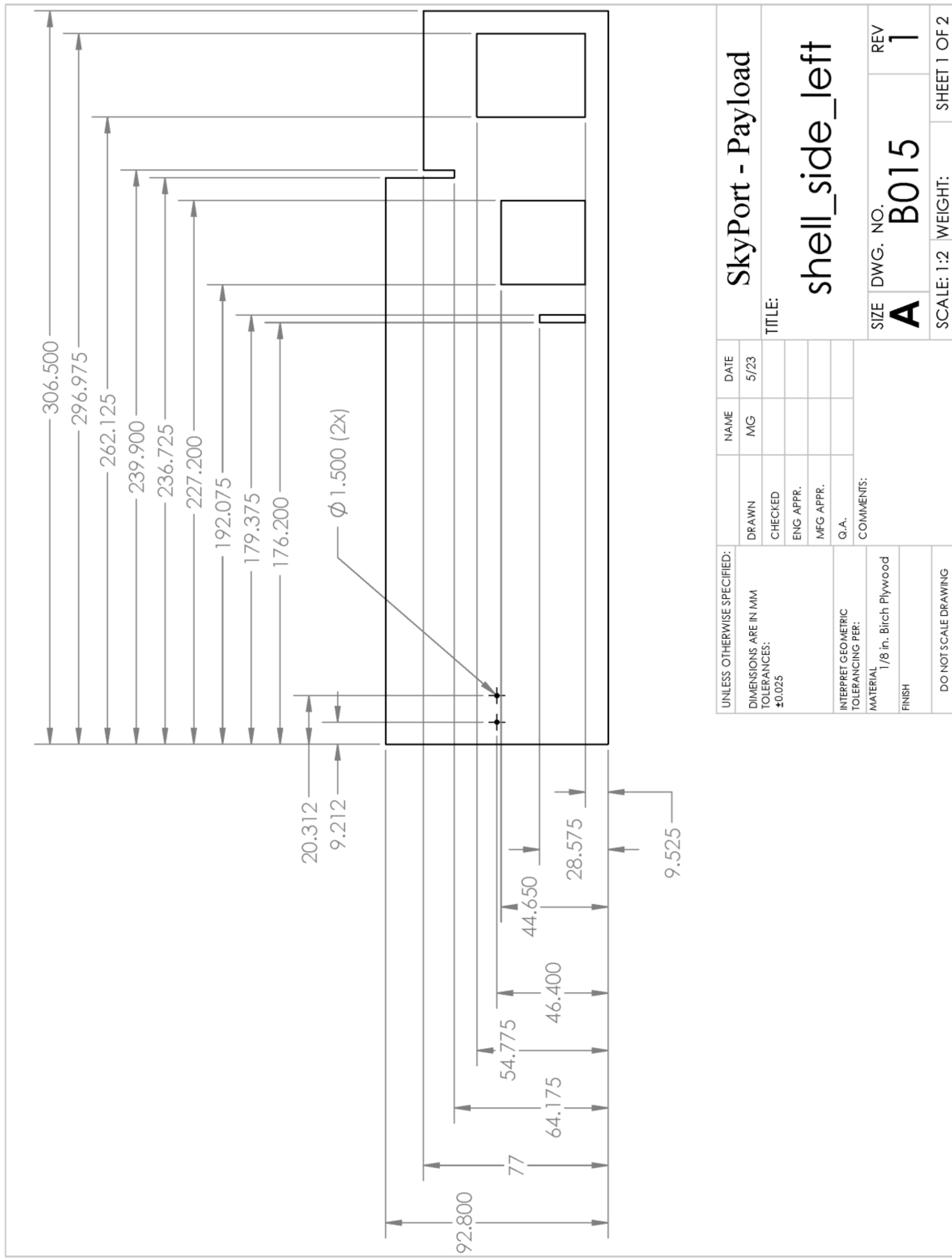


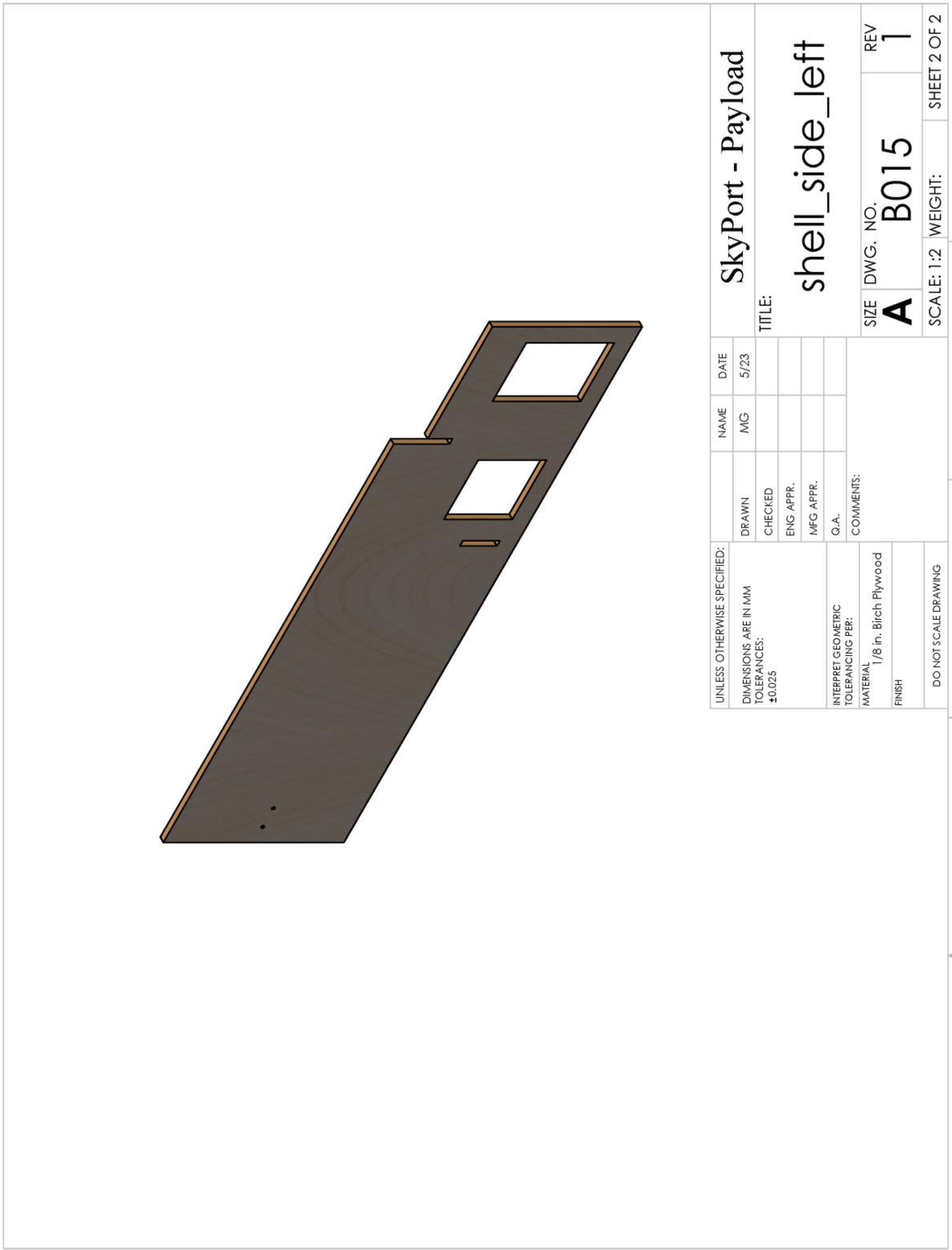
SkyPort - Payload
TITLE:
shell_cap_sides
SIZE
A
DWG. NO.
B012
REV
4
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Ø1.500 (2X)
24.400
18.300
3.175
42.438
50.362
92.800
1
2
3
4
5

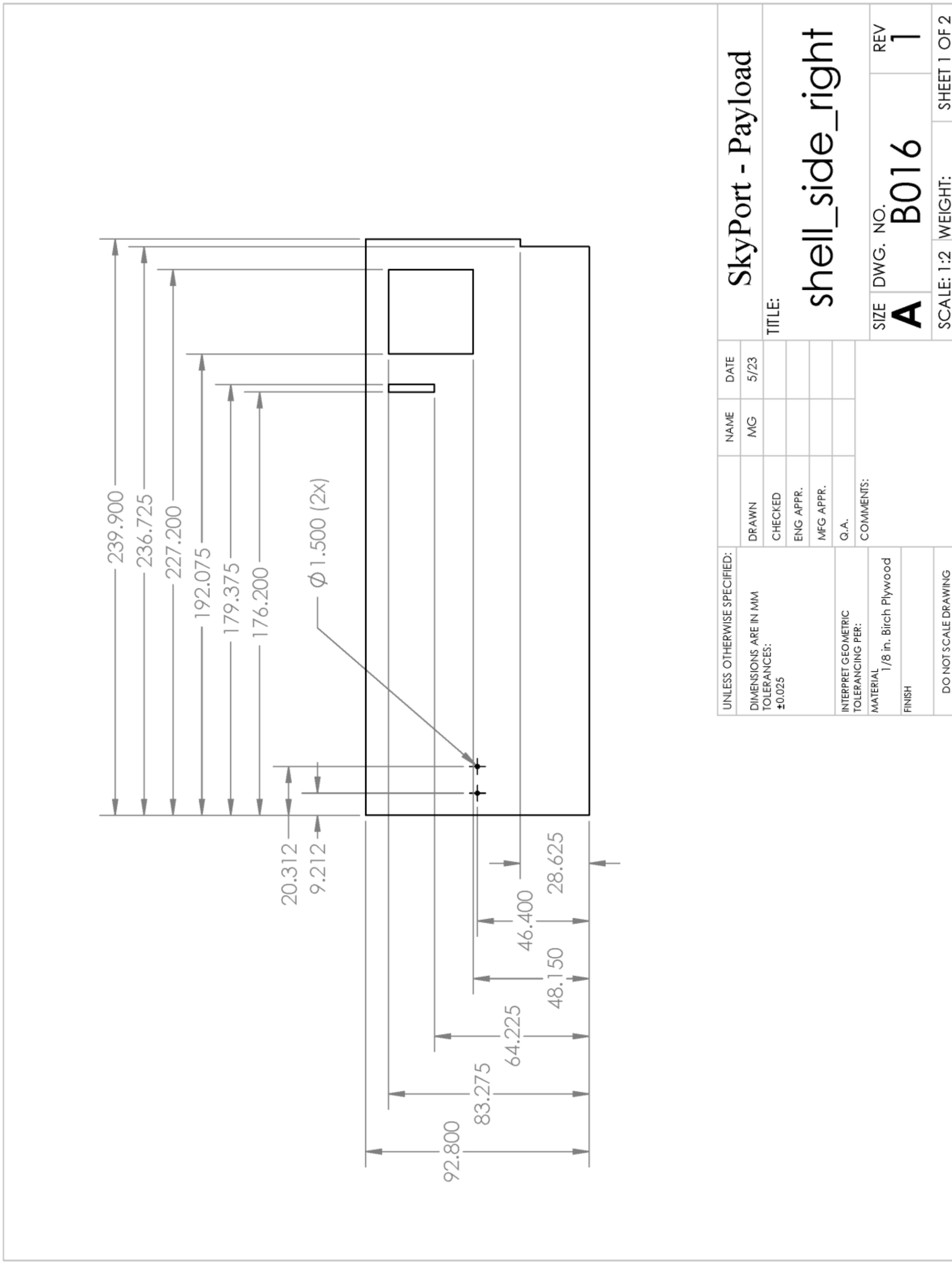


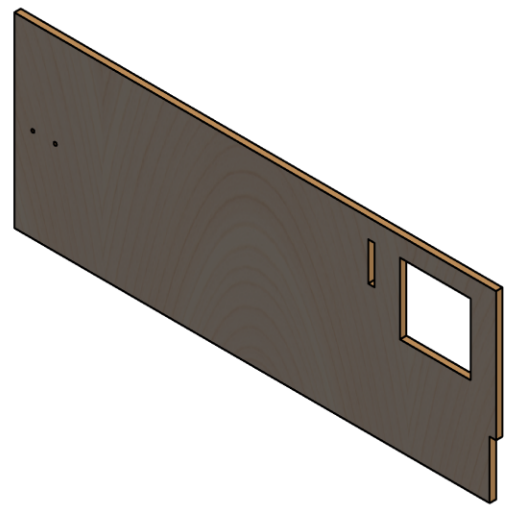

| | | | | |
|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | SkyPort - Payload |
| DIMENSIONS ARE IN MM<br>TOLERANCES:<br>±0.025 | DRAWN | MG | 5/23 | TITLE: |
| | CHECKED | | | shell_cap_top |
| | ENG APPR. | | | |
| | MFG APPR. | | | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | | |
| MATERIAL 1/8 in. Birch Plywood | COMMENTS: | | | SIZE A | DWG. NO. B013 | REV 3 |
| FINISH | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1 |


58.900
42.400
34.400
27.825
26.400
22.051
12.825
7.051
3.175
10
25.975
29.875
35.875
45.025
54.550
57.725
3.175
SkyPort - Payload
TITLE:
shell_front
SIZE A
DWG. NO. B014
REV 4
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN MG 5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING


306.500
296.975
262.125
239.900
236.725
227.200
192.075
179.375
176.200
Ø1.500 (2x)
20.312
9.212
28.575
9.525
44.650
46.400
54.775
64.175
77
92.800
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
shell_side_left
SIZE
A
DWG. NO.
B015
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 2

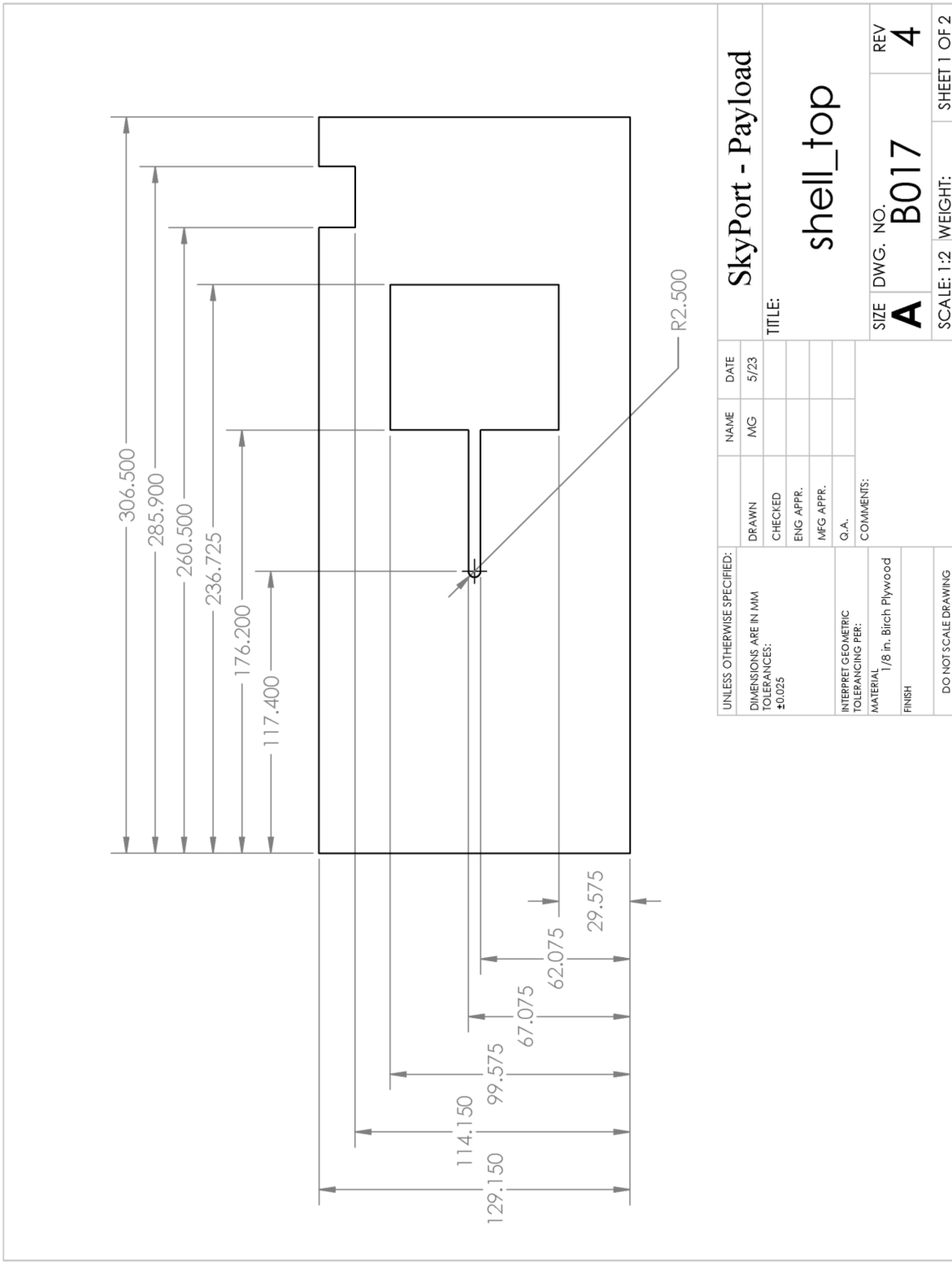

SkyPort - Payload
TITLE:
shell_side_left
SIZE A
DWG. NO. B015
REV 1
SCALE: 1:2
WEIGHT:
SHEET 2 OF 2
NAME
DATE
DRAWN MG 5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
1
2
3
4
5

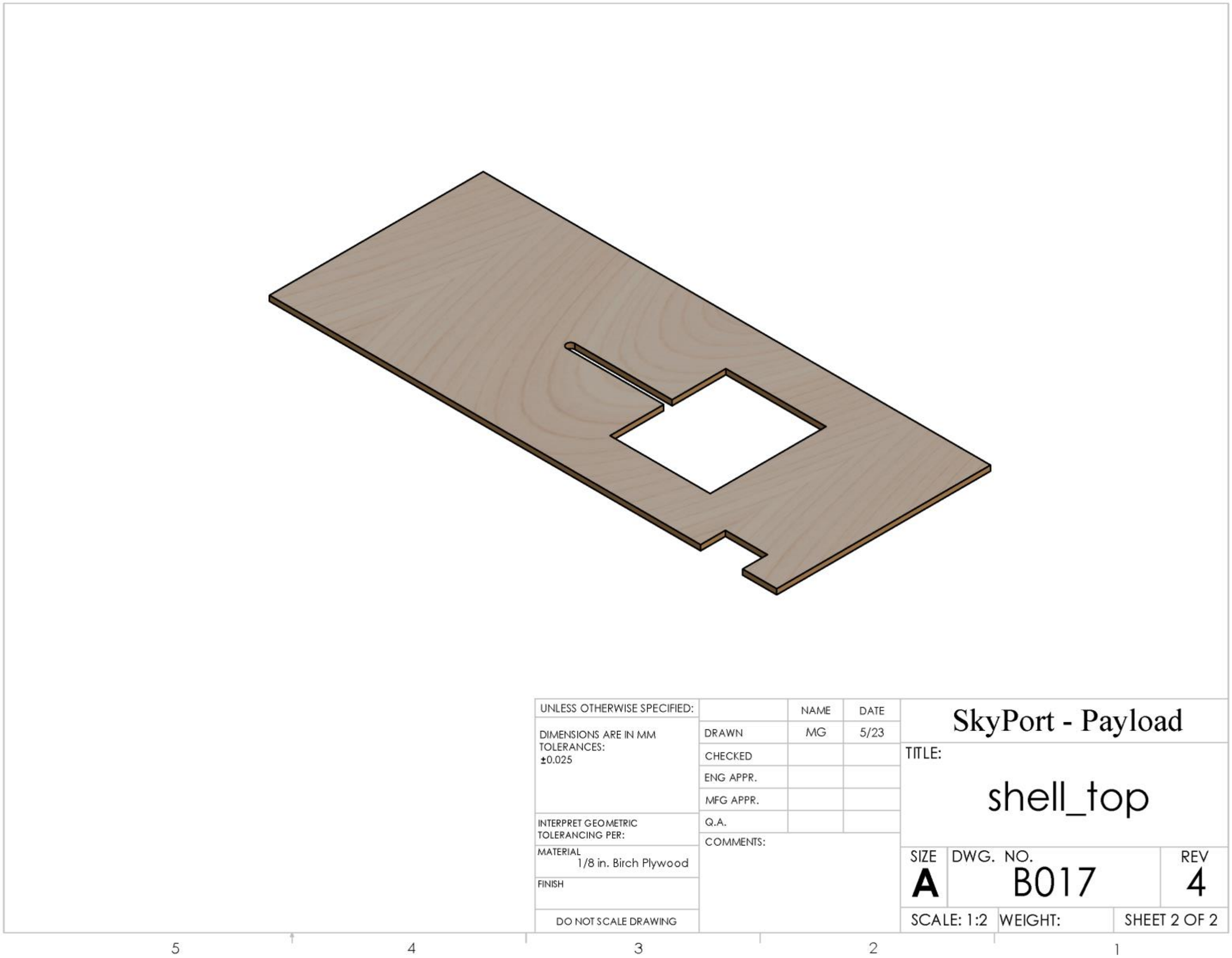

239.900
236.725
227.200
192.075
179.375
176.200
Ø1.500 (2X)
20.312
9.212
28.625
46.400
48.150
64.225
83.275
92.800
SkyPort - Payload
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
shell_side_right
SIZE
A
DWG. NO.
B016
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 2
1
2
3
4
5

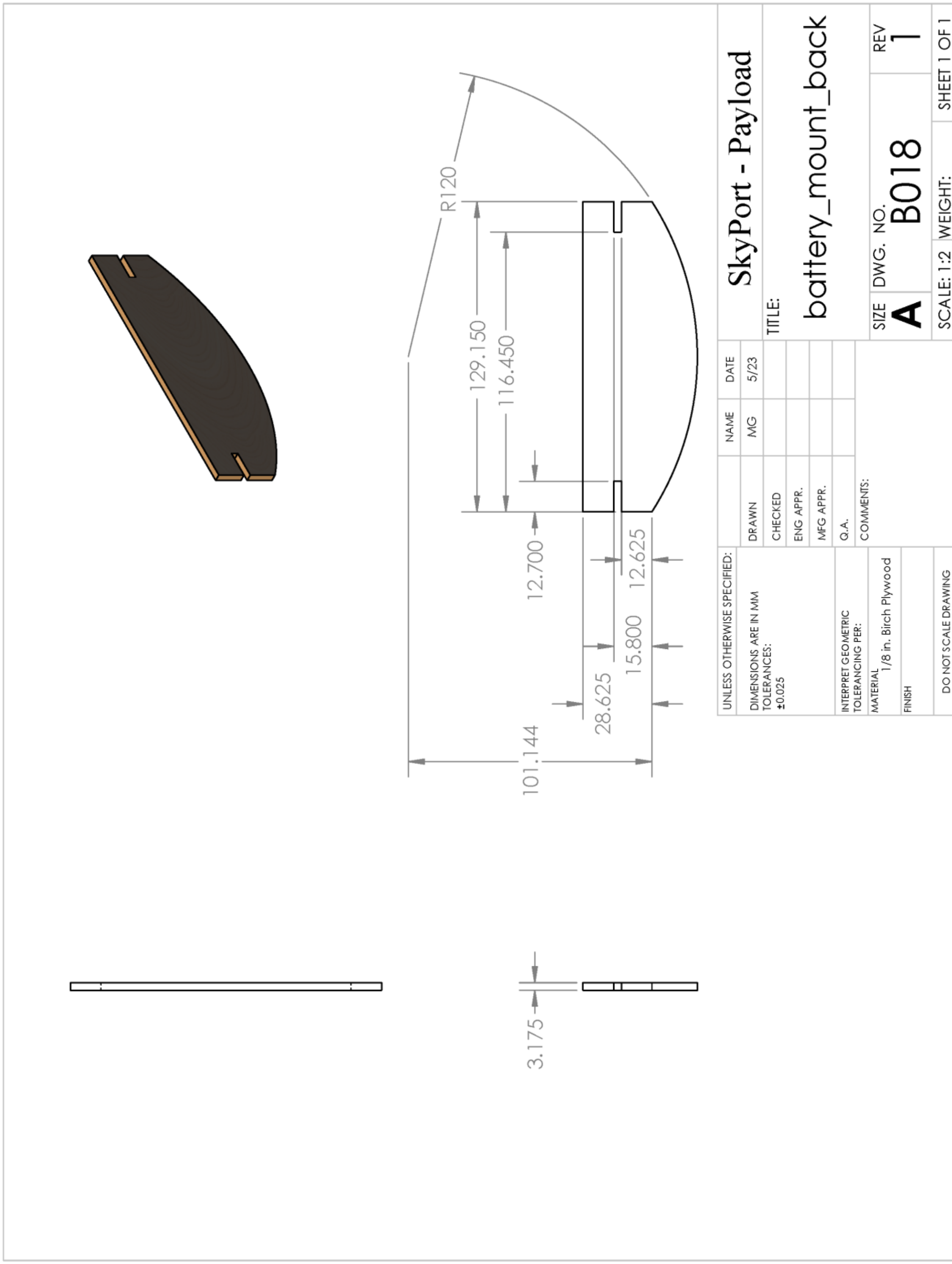


| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | SkyPort - Payload |
|---|---|---|---|---|
| DIMENSIONS ARE IN MM<br>TOLERANCES:<br>±0.025 | DRAWN | MG | 5/23 | TITLE: |
| | CHECKED | | | shell_side_right |
| | ENG APPR. | | | |
| | MFG APPR. | | | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | | |
| MATERIAL<br>1/8 in. Birch Plywood | COMMENTS: | | | SIZE A · DWG. NO. B016 · REV 1 |
| FINISH | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:2 · WEIGHT: · SHEET 2 OF 2 |

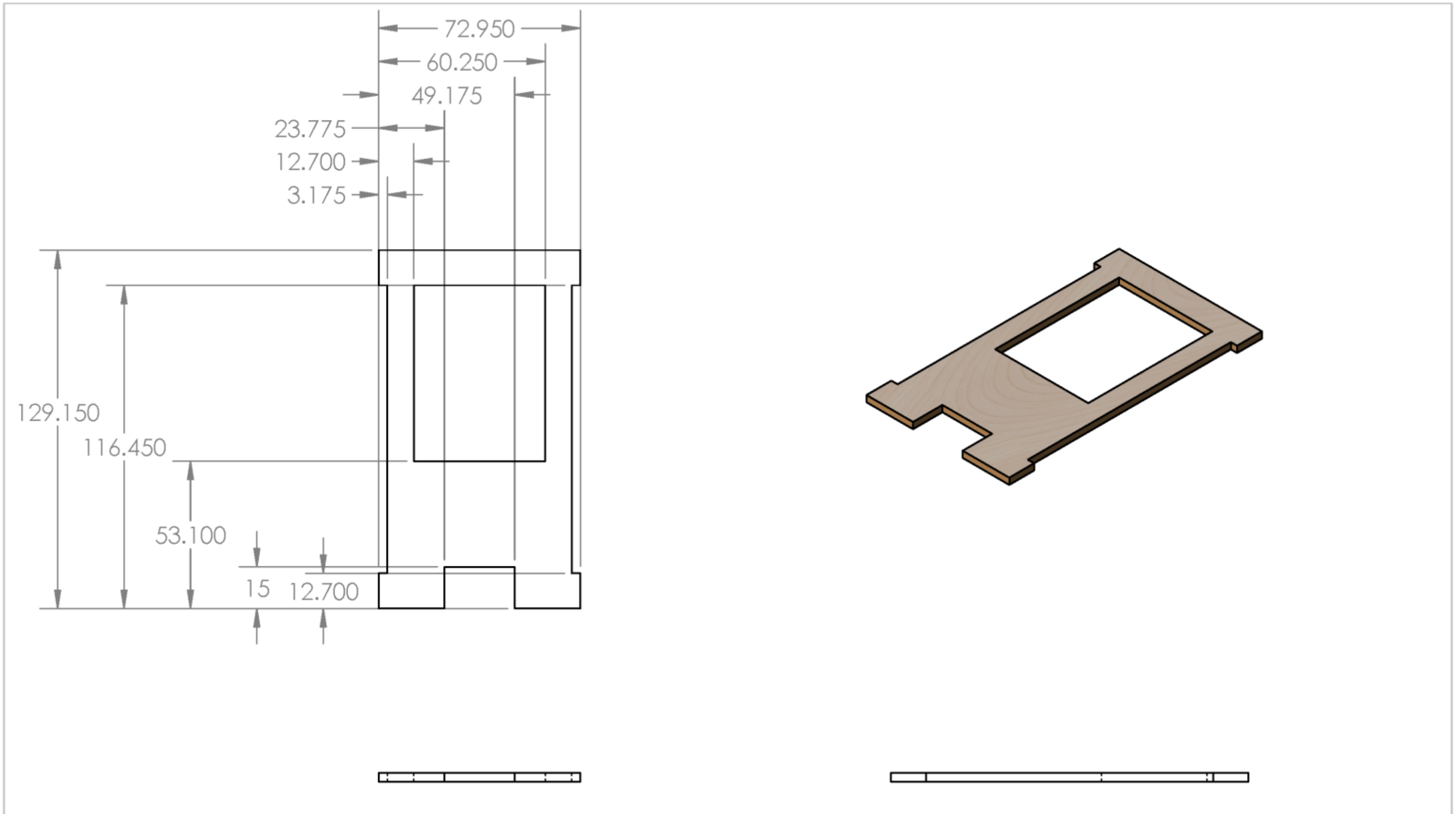
5 4 3 2 1


306.500
285.900
260.500
236.725
176.200
117.400
R2.500
29.575
62.075
67.075
99.575
114.150
129.150
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
shell_top
SIZE
A
DWG. NO.
B017
REV
4
SCALE: 1:2
WEIGHT:
SHEET 1 OF 2
1
2
3
4
5


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
shell_top
SIZE
A
DWG. NO.
B017
REV
4
SCALE: 1:2
WEIGHT:
SHEET 2 OF 2
5
4
3
2
1

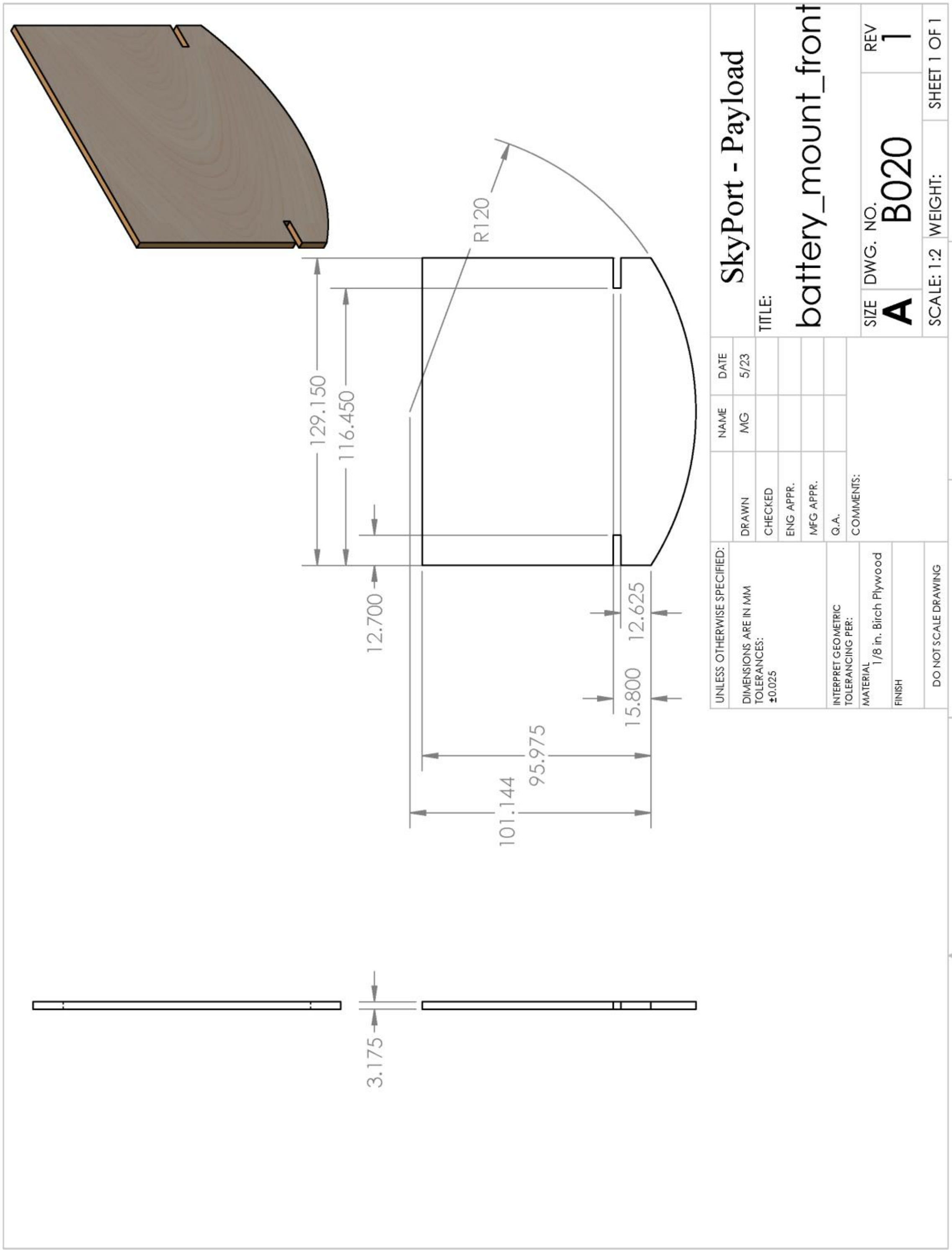


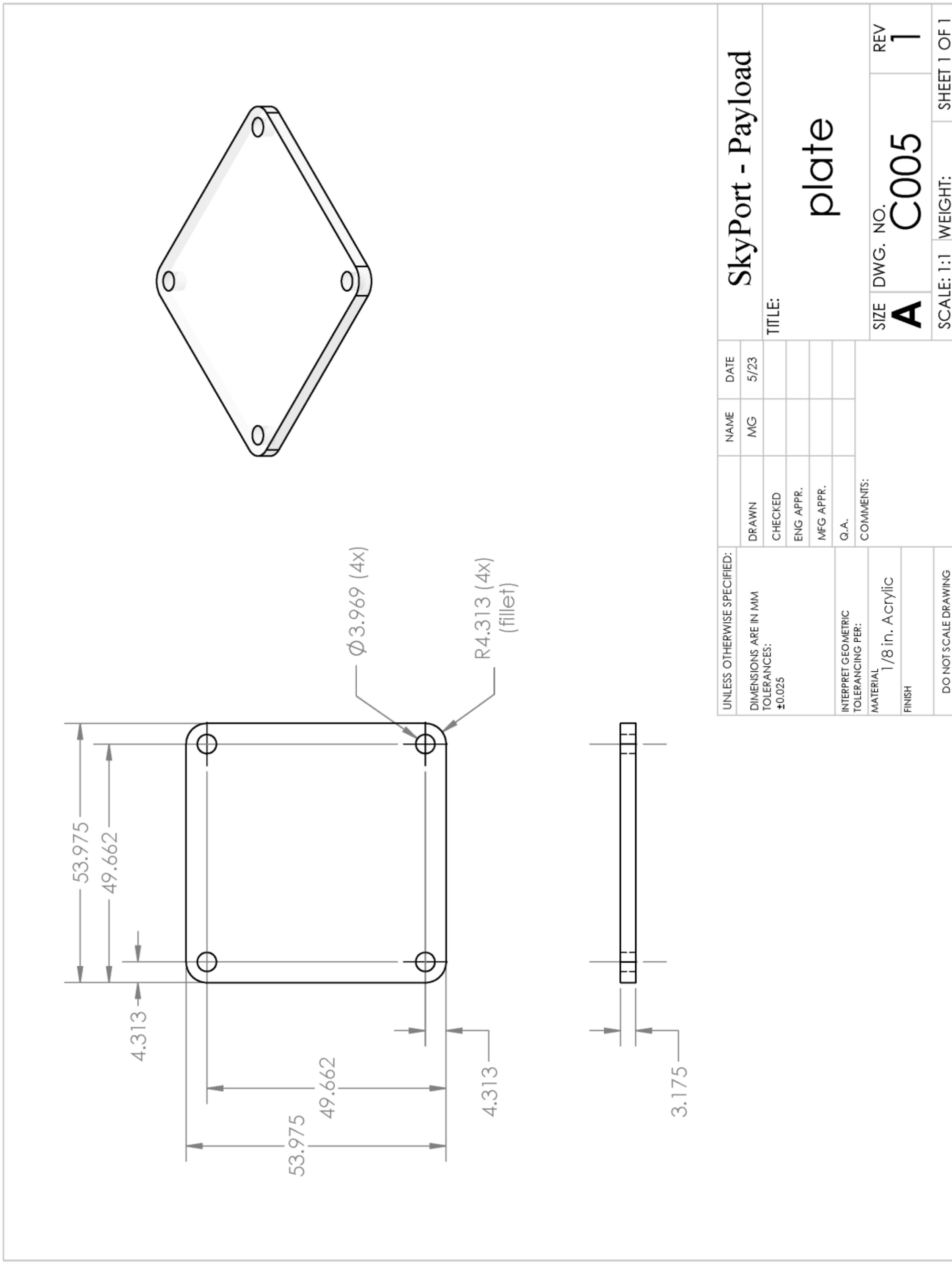
SkyPort - Payload
TITLE:
battery_mount_back
SIZE
A
DWG. NO.
B018
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R120
129.150
116.450
12.700
12.625
15.800
28.625
101.144
3.175
1
2
3
4
5

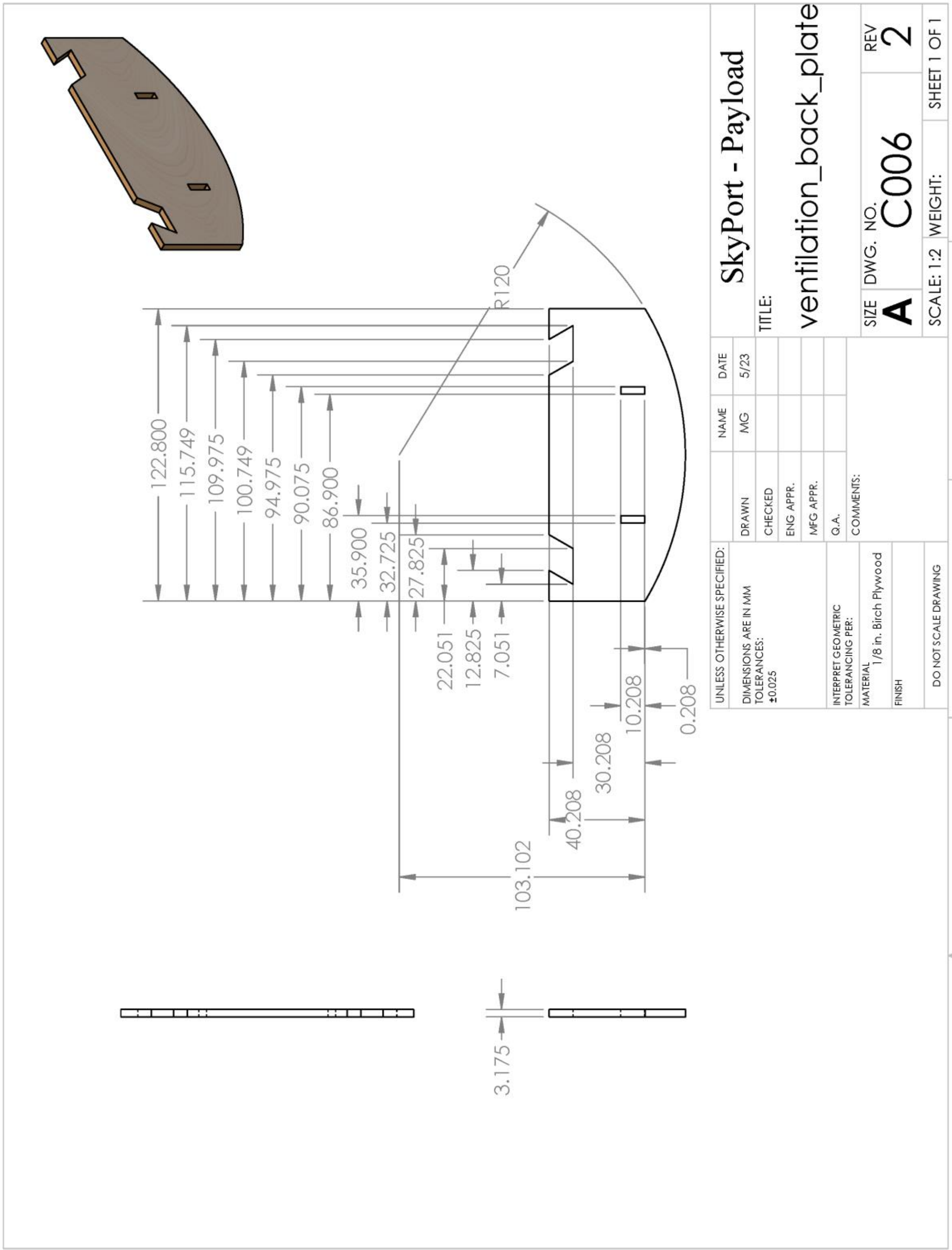



| | | | | |
|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | SkyPort - Payload |
| DIMENSIONS ARE IN MM TOLERANCES: ±0.025 | DRAWN | MG | 5/23 | TITLE: battery_mount_bottom |
| | CHECKED | | | |
| | ENG APPR. | | | |
| | MFG APPR. | | | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | | | |
| MATERIAL 1/8 in. Birch Plywood | COMMENTS: | | | SIZE A DWG. NO. B019 REV 1 |
| FINISH | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:2 WEIGHT: SHEET 1 OF 1 |

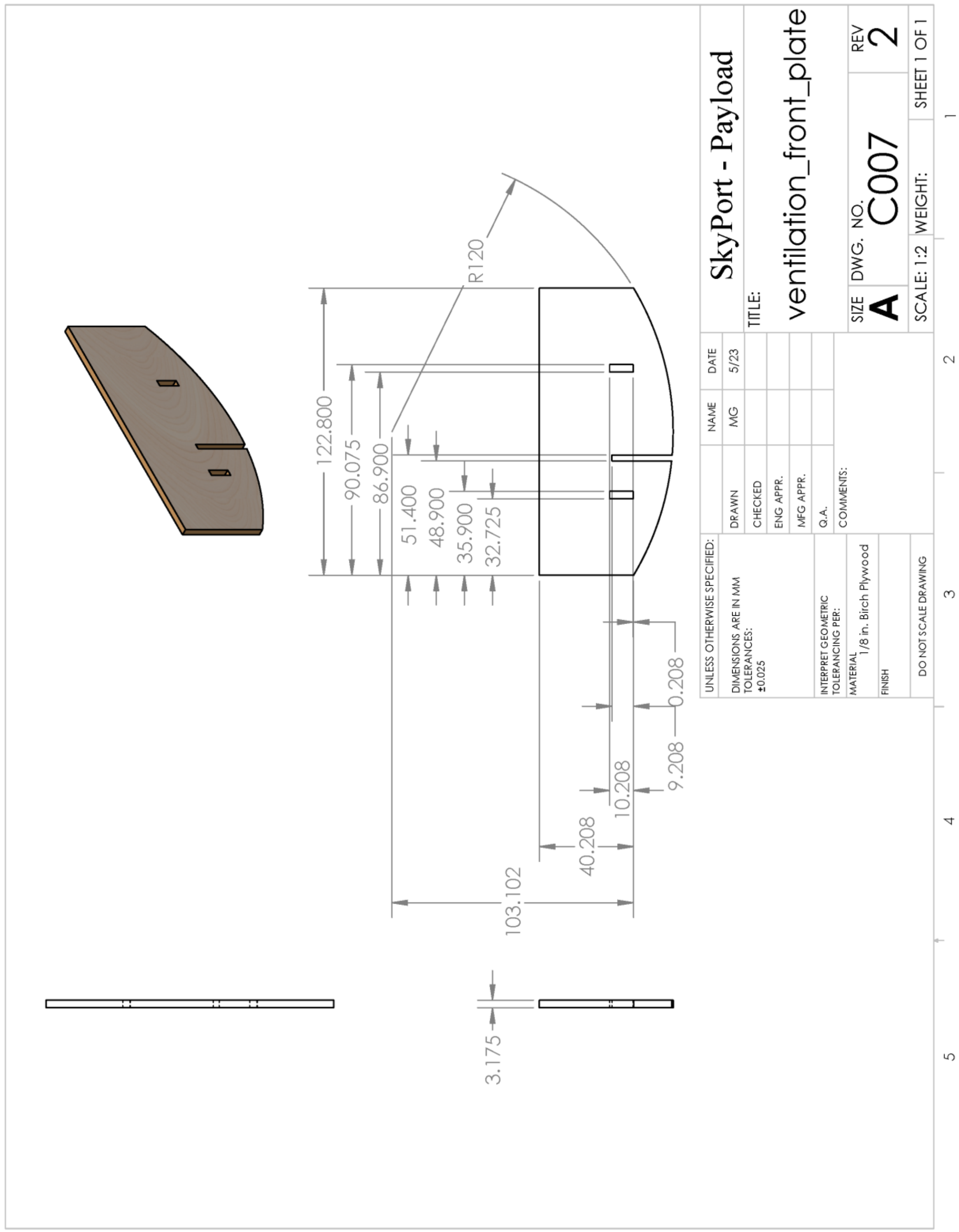
5 4 3 2 1

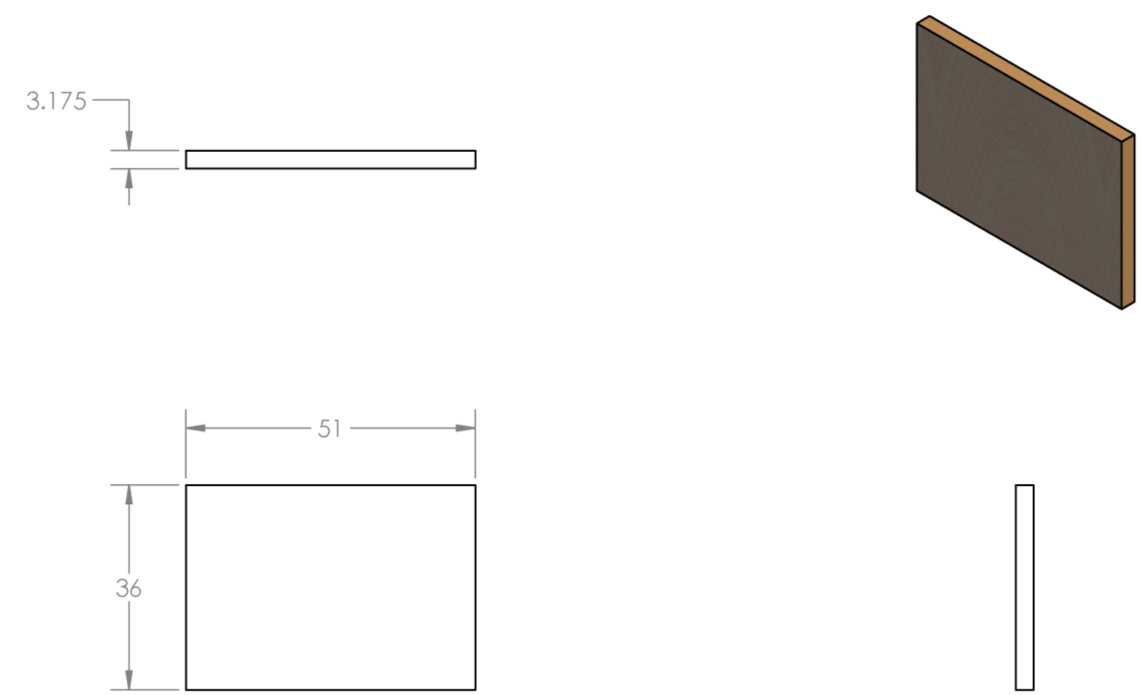

SkyPort - Payload
TITLE:
battery_mount_front
SIZE
A
DWG. NO.
B020
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R120
129.150
116.450
12.700
12.625
15.800
95.975
101.144
3.175
1
2
3
4
5


SkyPort - Payload
TITLE:
plate
SIZE
A
DWG. NO.
C005
REV
1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Acrylic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Φ3.969 (4x)
R4.313 (4x)
(fillet)
53.975
49.662
4.313
49.662
53.975
4.313
3.175



SkyPort - Payload
TITLE:
ventilation_back_plate
SIZE
A
DWG. NO.
C006
REV
2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R120
122.800
115.749
109.975
100.749
94.975
90.075
86.900
35.900
32.725
27.825
22.051
12.825
7.051
10.208
0.208
30.208
40.208
103.102
3.175
1
2
3
4
5


SkyPort - Payload
TITLE:
ventilation_front_plate
SIZE A
DWG. NO. C007
REV 2
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN MG 5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R120
122.800
90.075
86.900
51.400
48.900
35.900
32.725
0.208
9.208
10.208
40.208
103.102
3.175




UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | MG | 5/23 |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

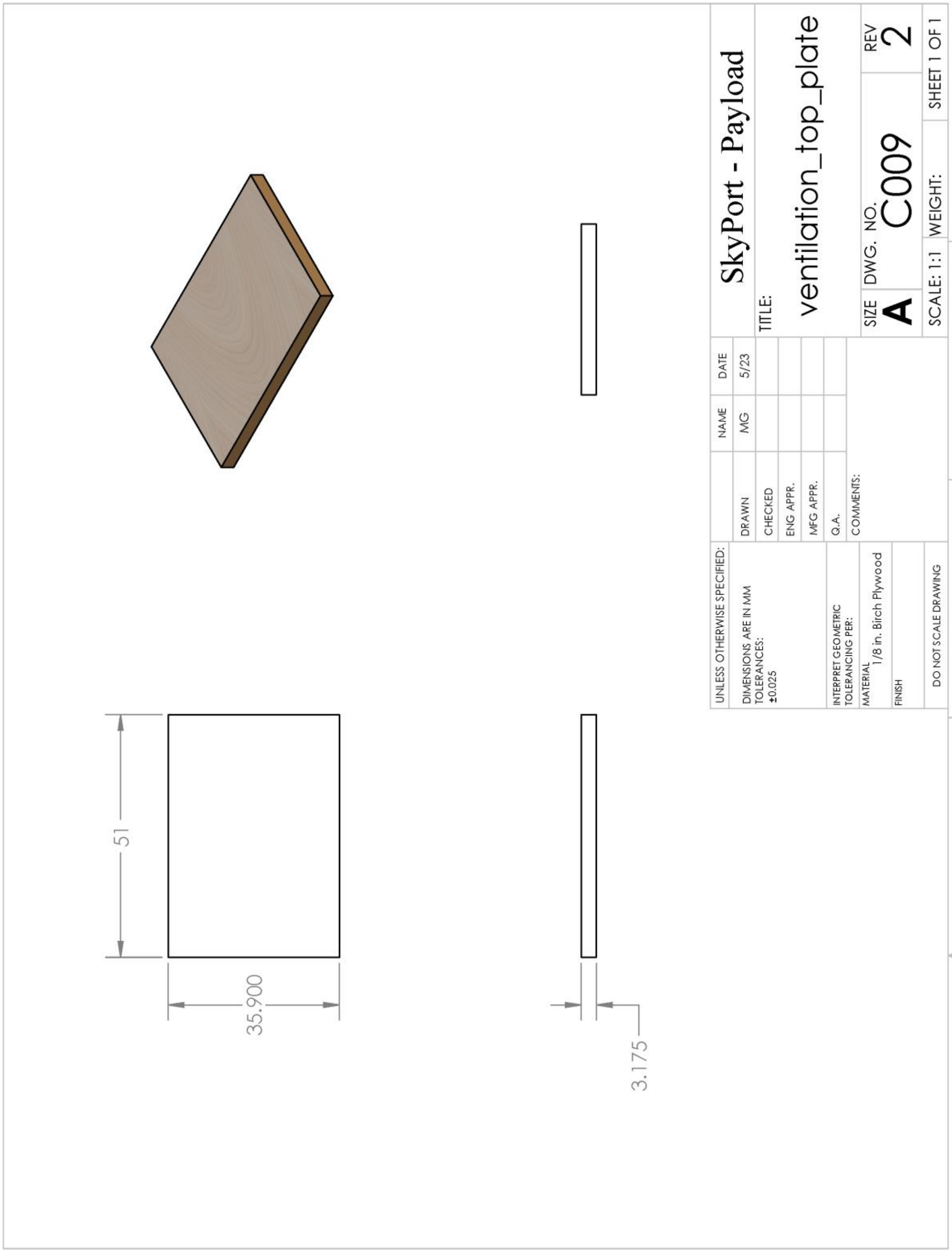
SkyPort - Payload

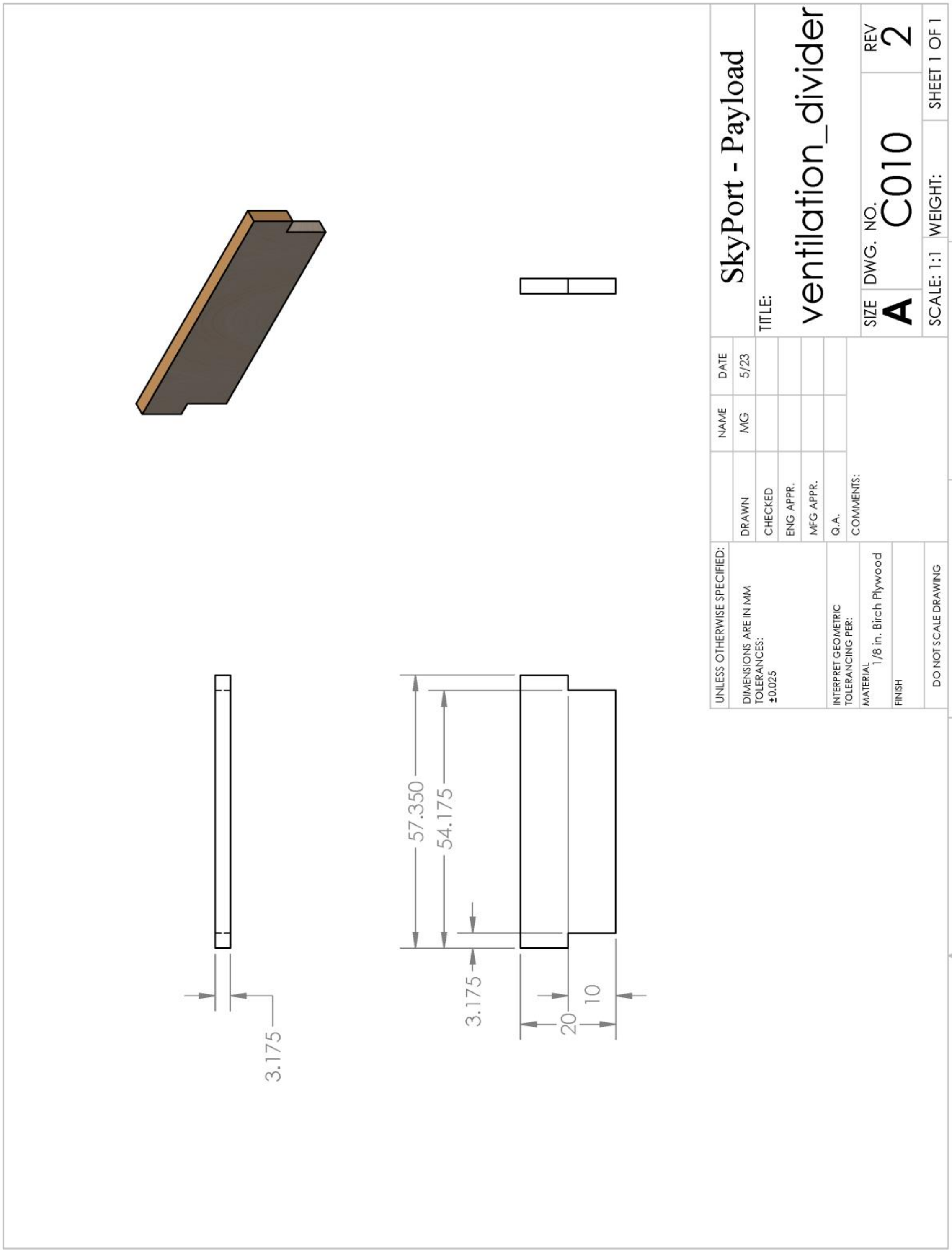
TITLE:
ventilation_side_plate

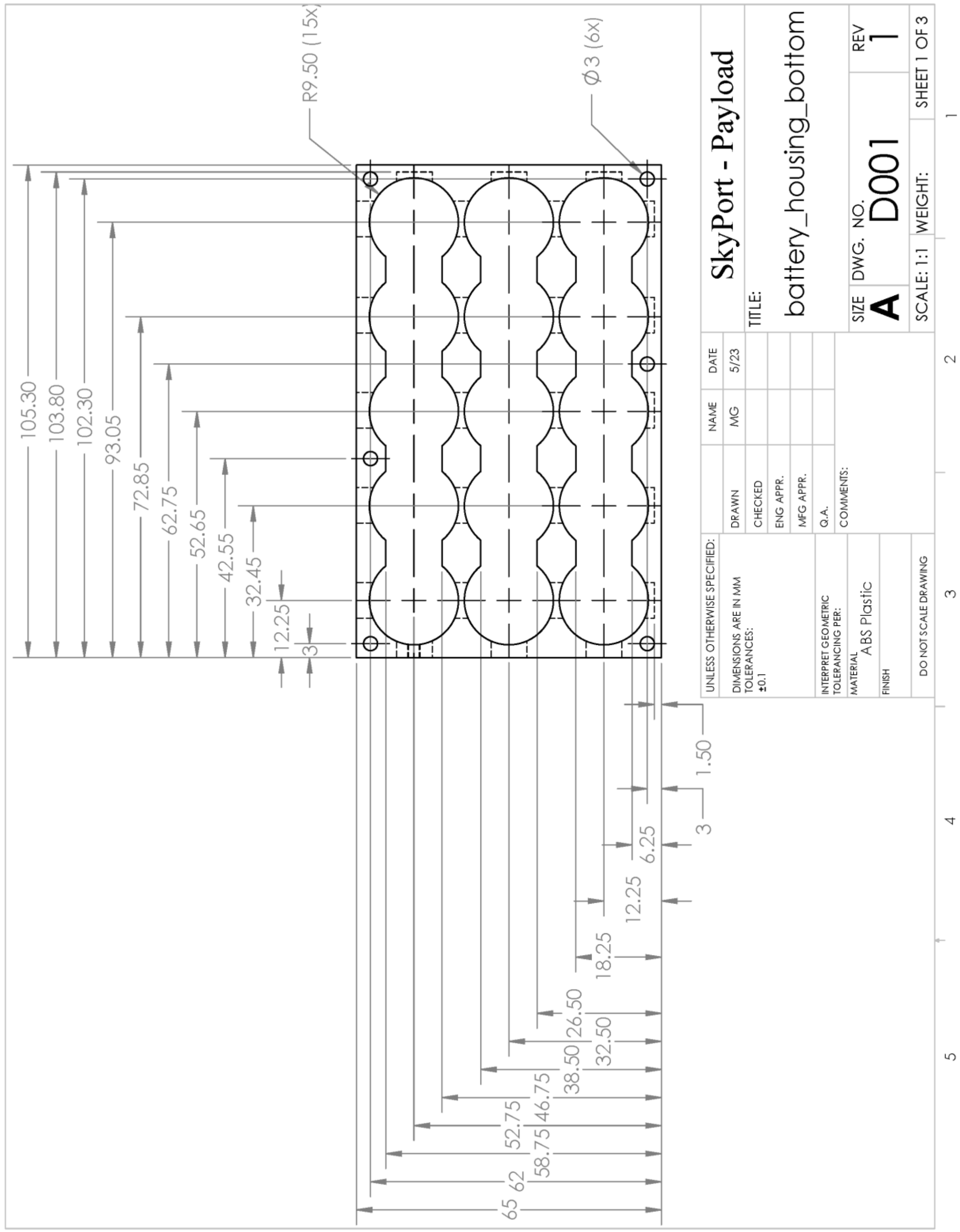
SIZE A | DWG. NO. C008 | REV 2

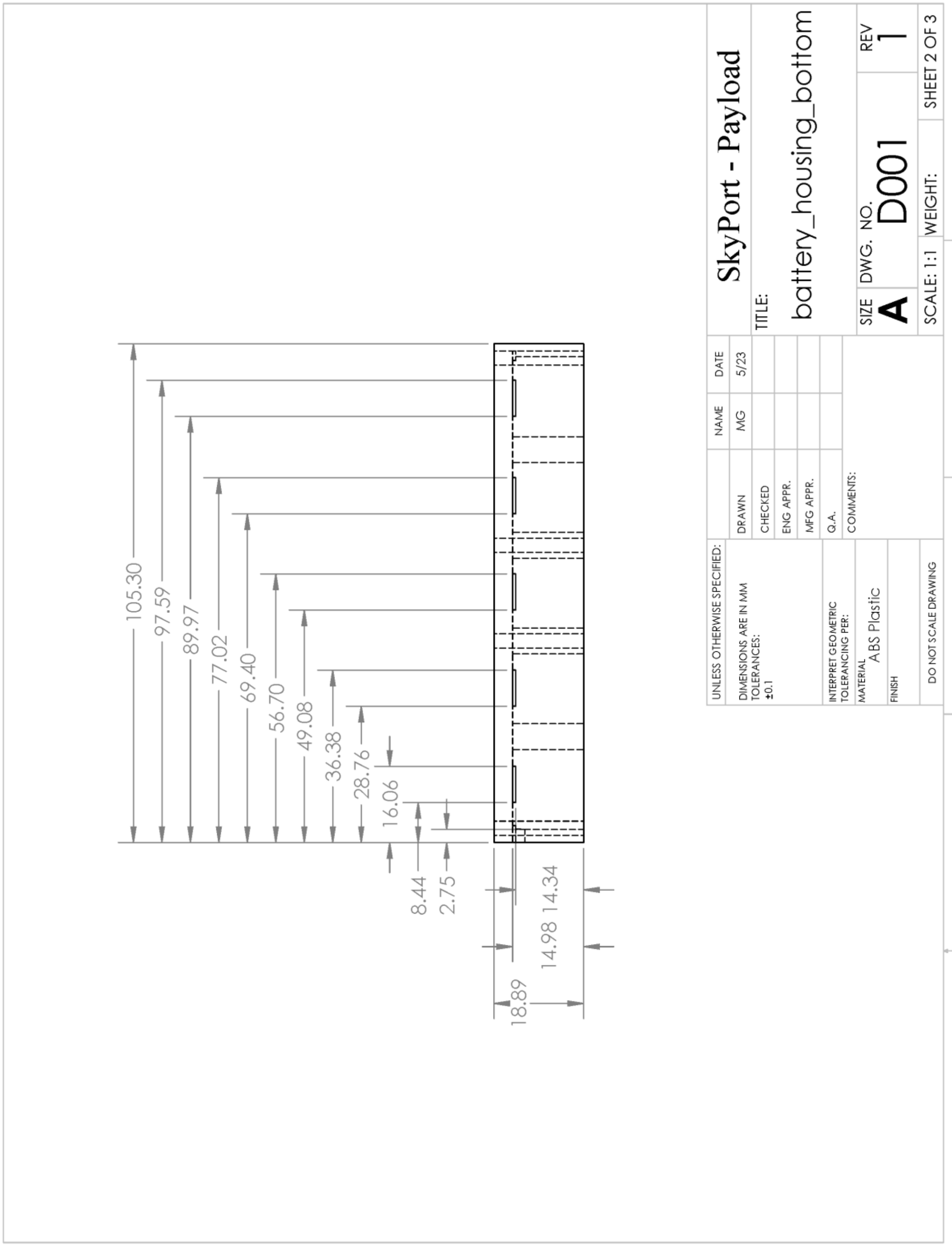
SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

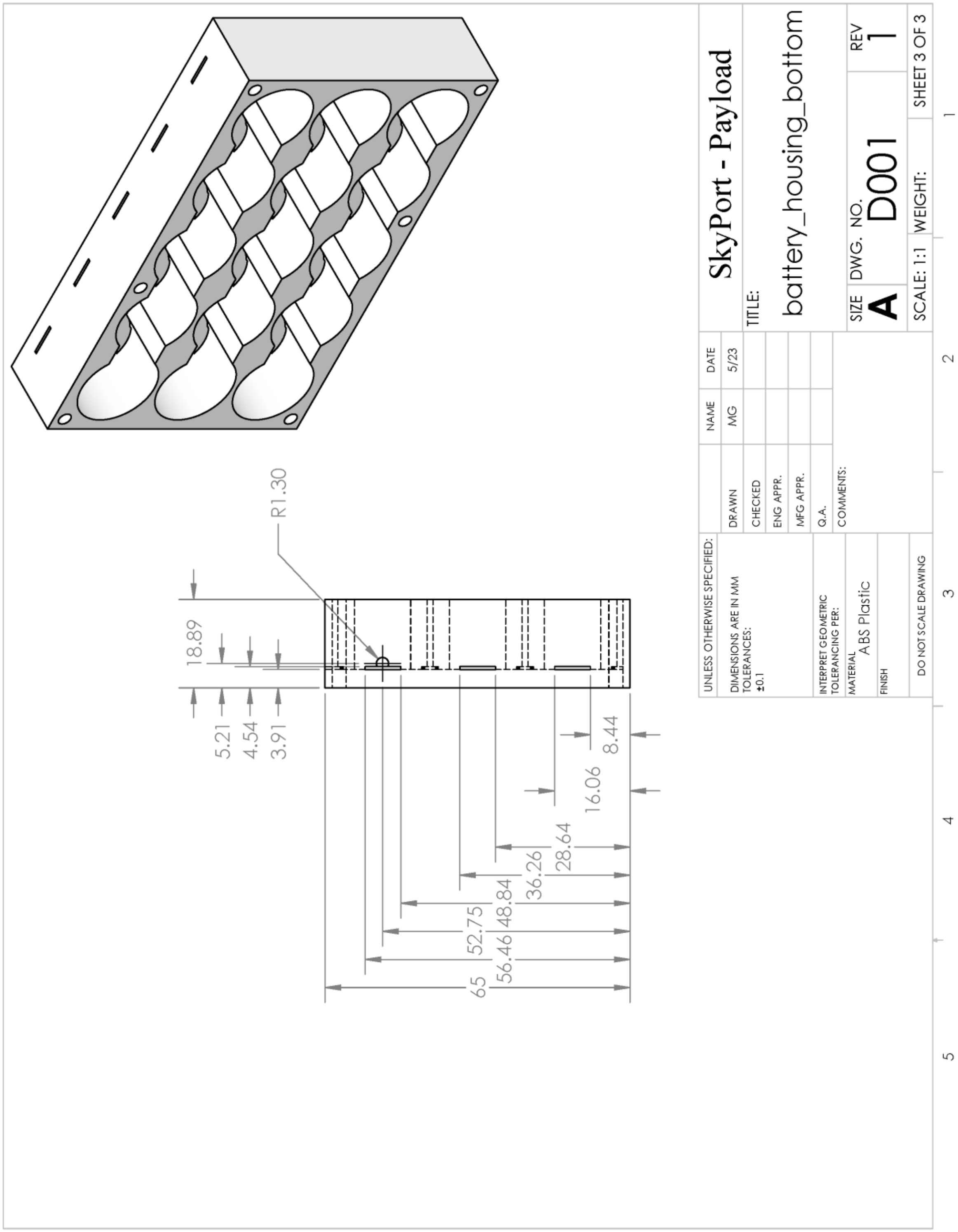
5 4 3 2 1


51
35.900
3.175
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
ventilation_top_plate
SIZE
A
DWG. NO.
C009
REV
2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
1
2
3
4
5

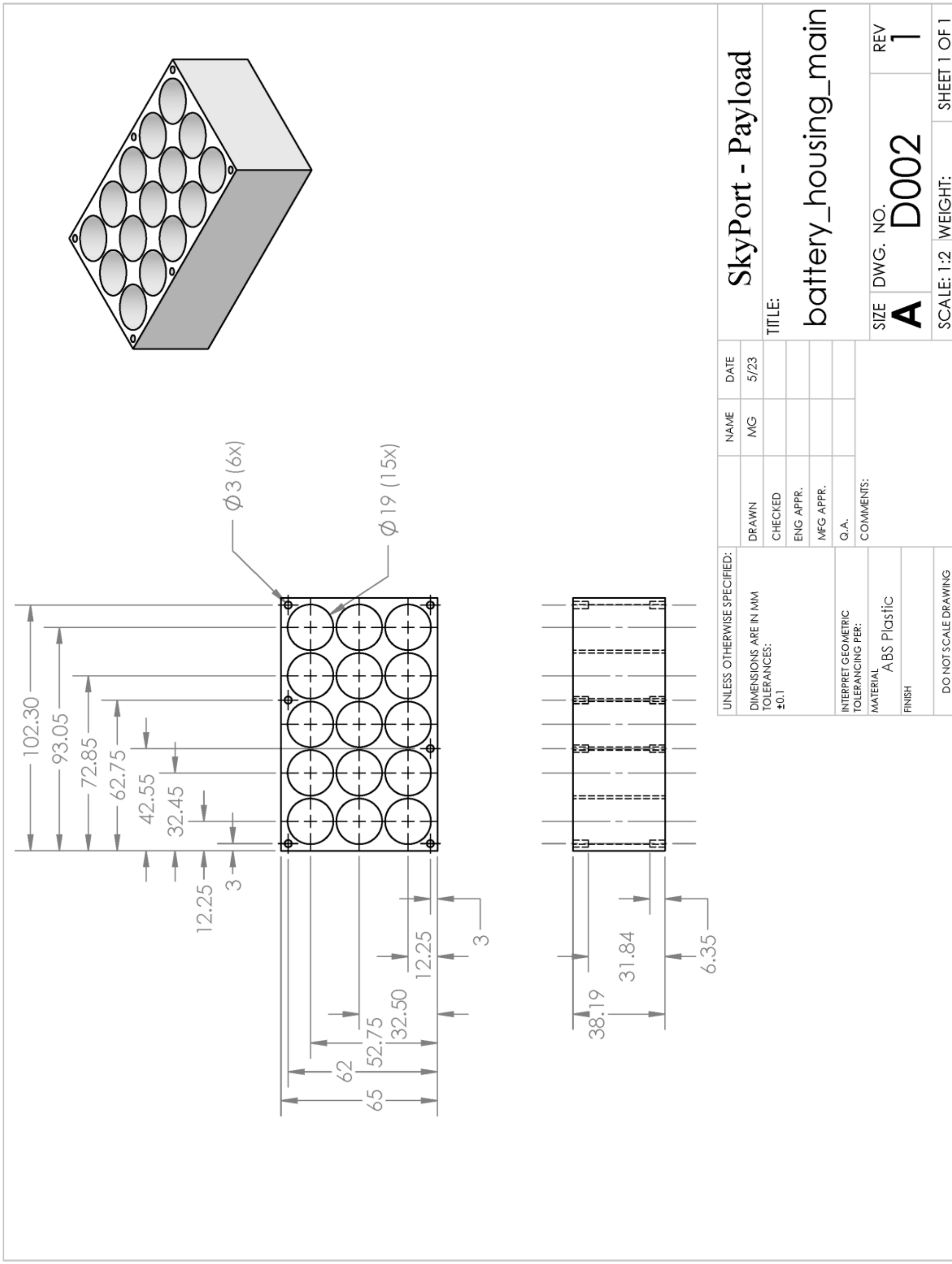

3.175
57.350
54.175
3.175
20
10
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.025
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
1/8 in. Birch Plywood
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
ventilation_divider
SIZE
A
DWG. NO.
C010
REV
2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1


SkyPort - Payload
TITLE:
battery_housing_bottom
SIZE A
DWG. NO. D001
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 3
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R9.50 (15x)
Ø3 (6x)
105.30
103.80
102.30
93.05
72.85
62.75
52.65
42.55
32.45
12.25
3
1.50
3
6.25
12.25
18.25
26.50
32.50
38.50
46.75
52.75
58.75
62
65

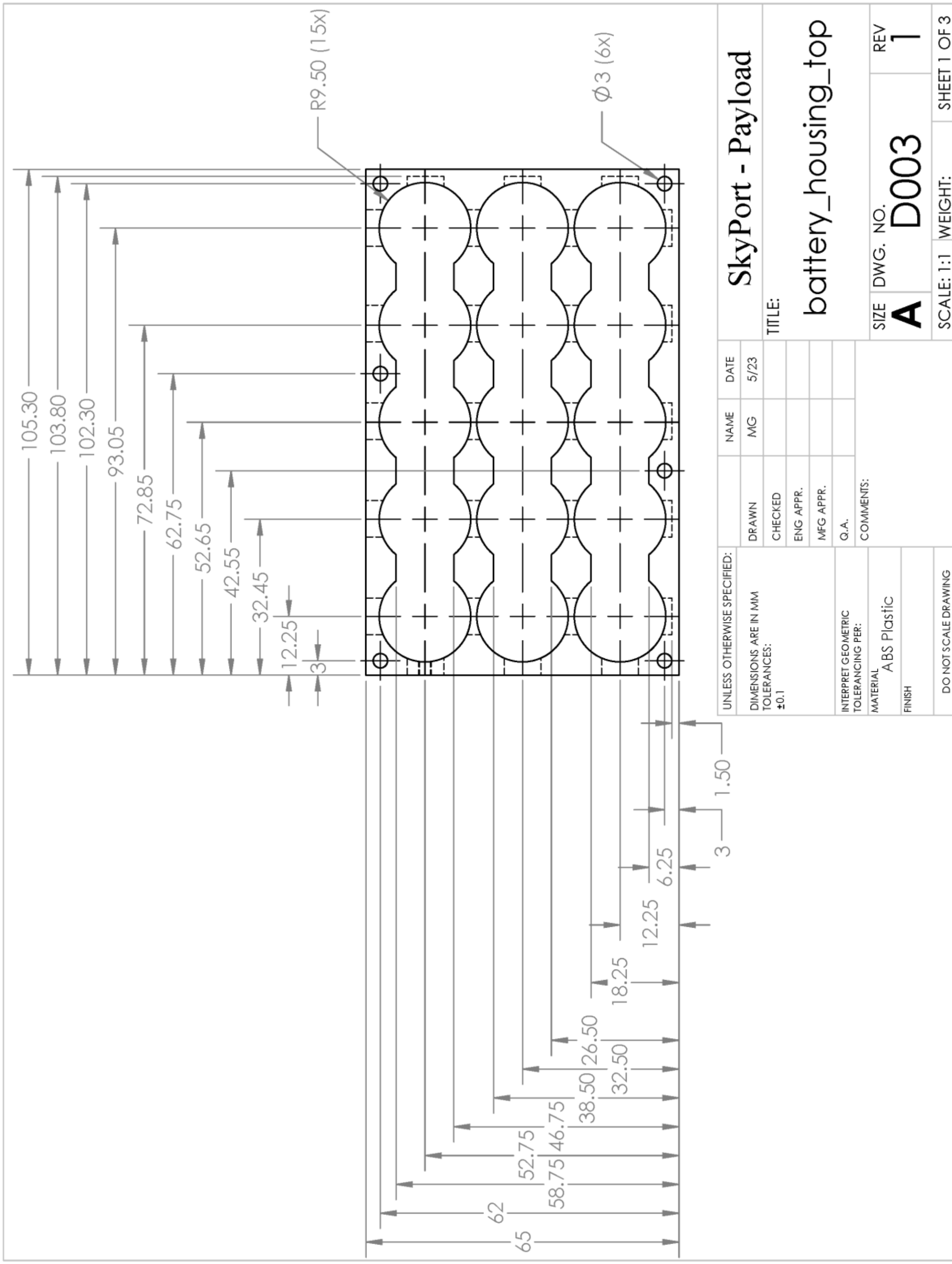

105.30
97.59
89.97
77.02
69.40
56.70
49.08
36.38
28.76
16.06
8.44
2.75
14.98
14.34
18.89
SkyPort - Payload
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
TITLE:
battery_housing_bottom
SIZE
A
DWG. NO.
D001
REV
1
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
1
2
3
4
5



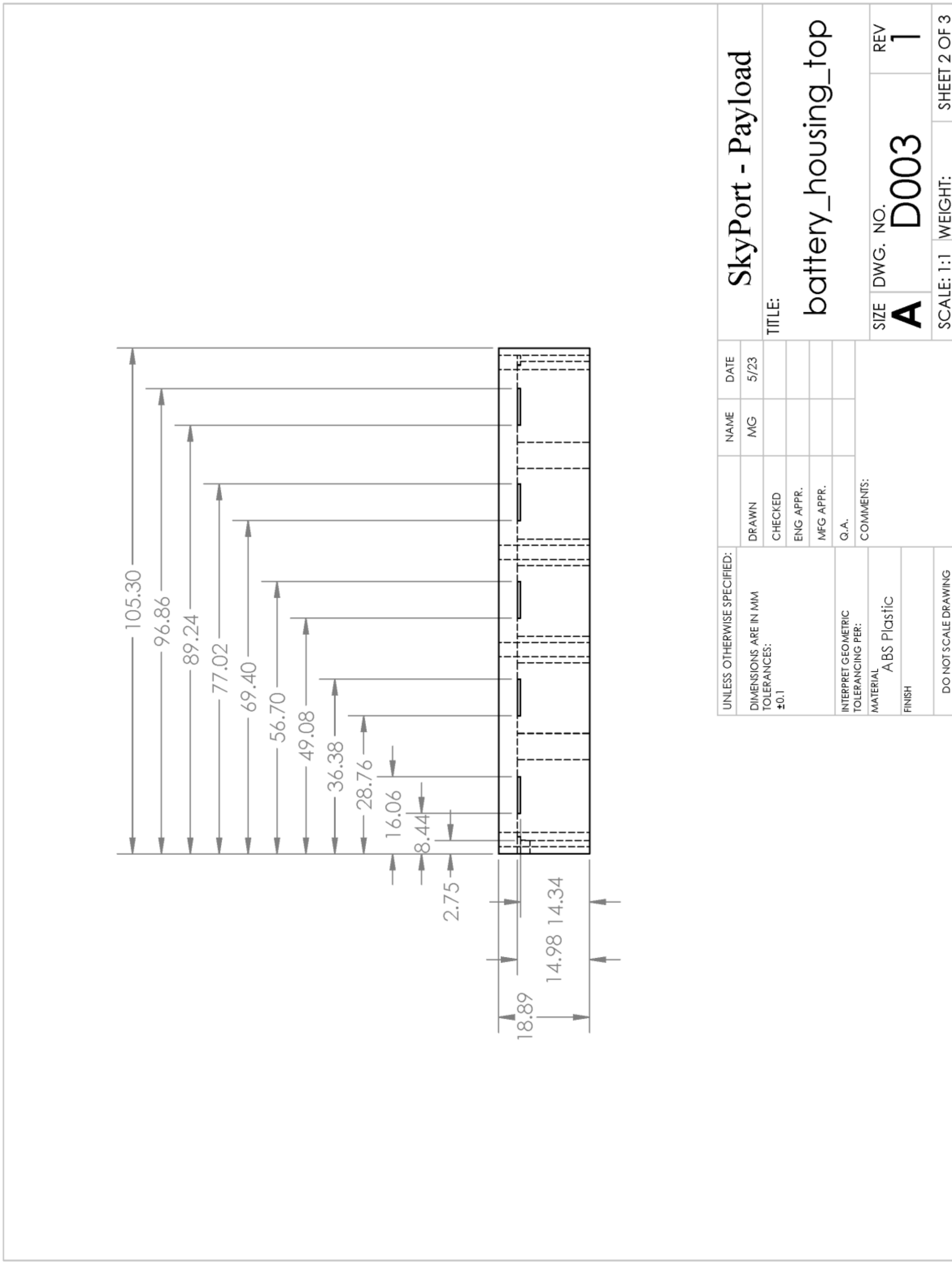
R1.30
18.89
5.21
4.54
3.91
8.44
16.06
28.64
36.26
48.84
52.75
56.46
65
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
SkyPort - Payload
TITLE:
battery_housing_bottom
SIZE
A
DWG. NO.
D001
REV
1
SCALE: 1:1
WEIGHT:
SHEET 3 OF 3
1
2
3
4
5

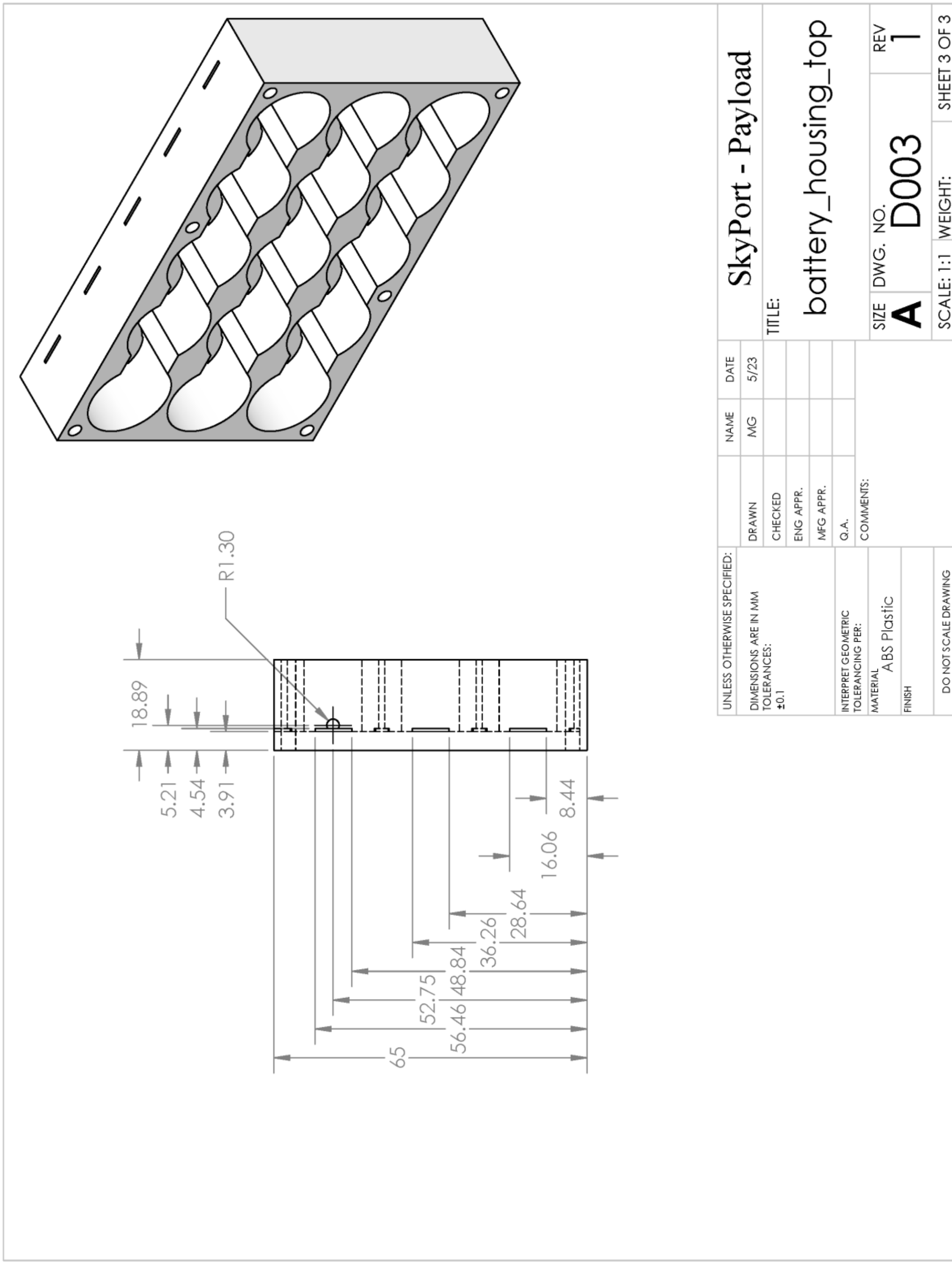


SkyPort - Payload
TITLE:
battery_housing_main
SIZE
A
DWG. NO.
D002
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Ø3 (6x)
Ø19 (15x)
102.30
93.05
72.85
62.75
42.55
32.45
12.25
3
65
62
52.75
32.50
12.25
3
38.19
31.84
6.35



SkyPort - Payload
TITLE:
battery_housing_top
SIZE A
DWG. NO. D003
REV 1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 3
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
R9.50 (15x)
Ø3 (6x)
105.30
103.80
102.30
93.05
72.85
62.75
52.65
42.55
32.45
12.25
3
1.50
3
6.25
12.25
18.25
26.50
32.50
38.50
46.75
52.75
58.75
62
65
1
2
3
4
5


SkyPort - Payload
TITLE:
battery_housing_top
SIZE A
DWG. NO. D003
REV 1
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
±0.1
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ABS Plastic
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MG
5/23
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
105.30
96.86
89.24
77.02
69.40
56.70
49.08
36.38
28.76
16.06
8.44
2.75
14.34
14.98
18.89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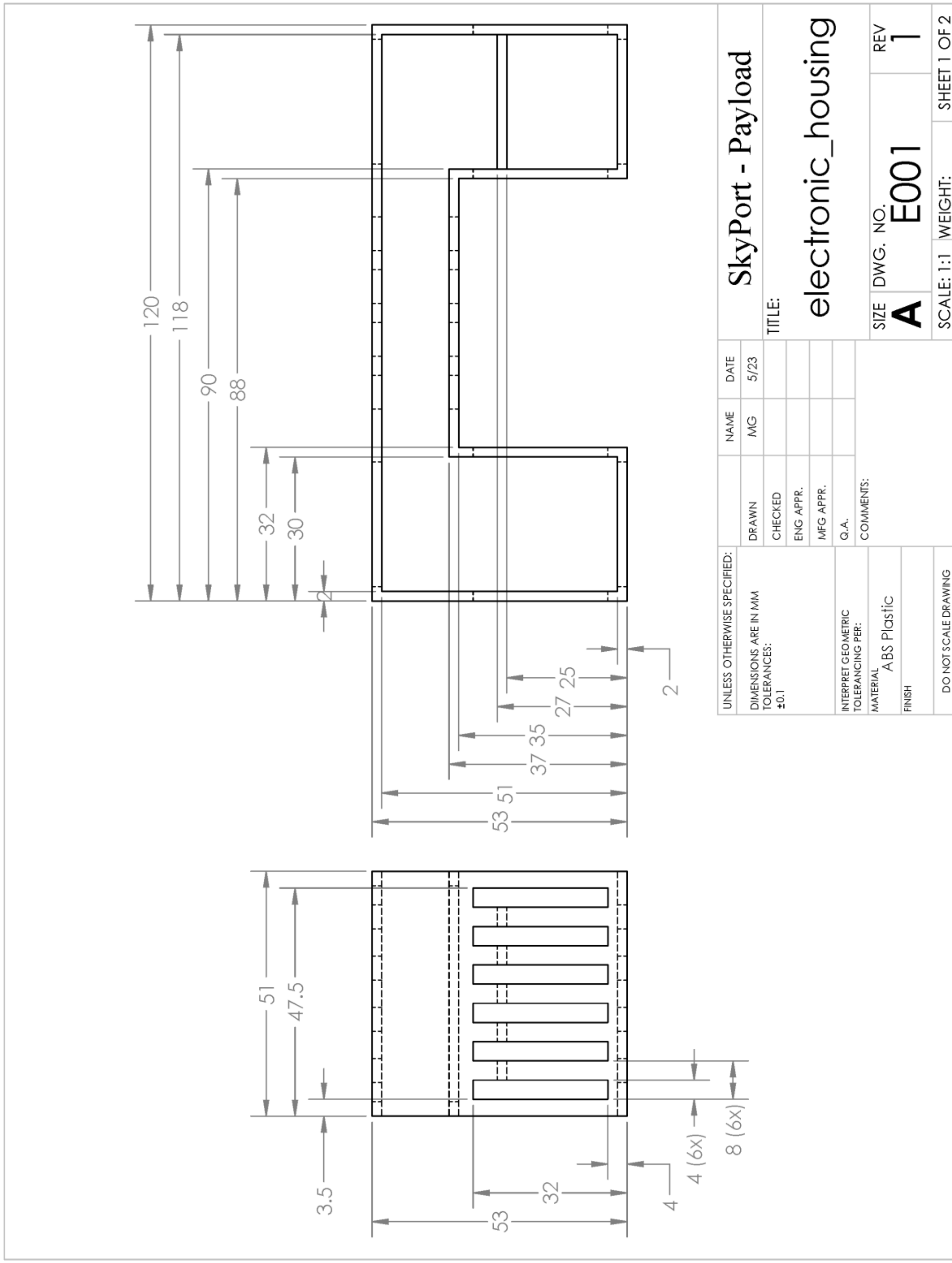
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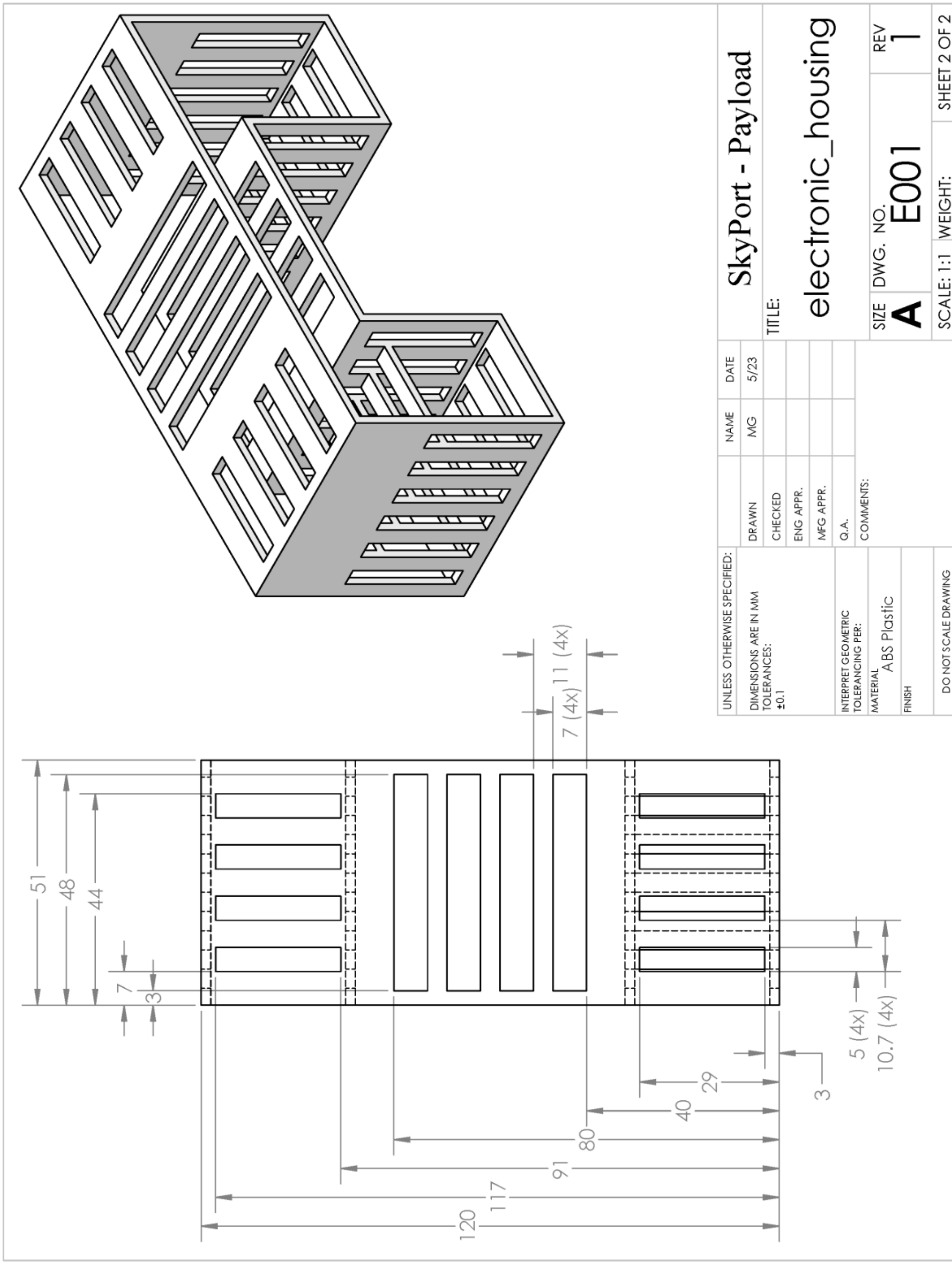
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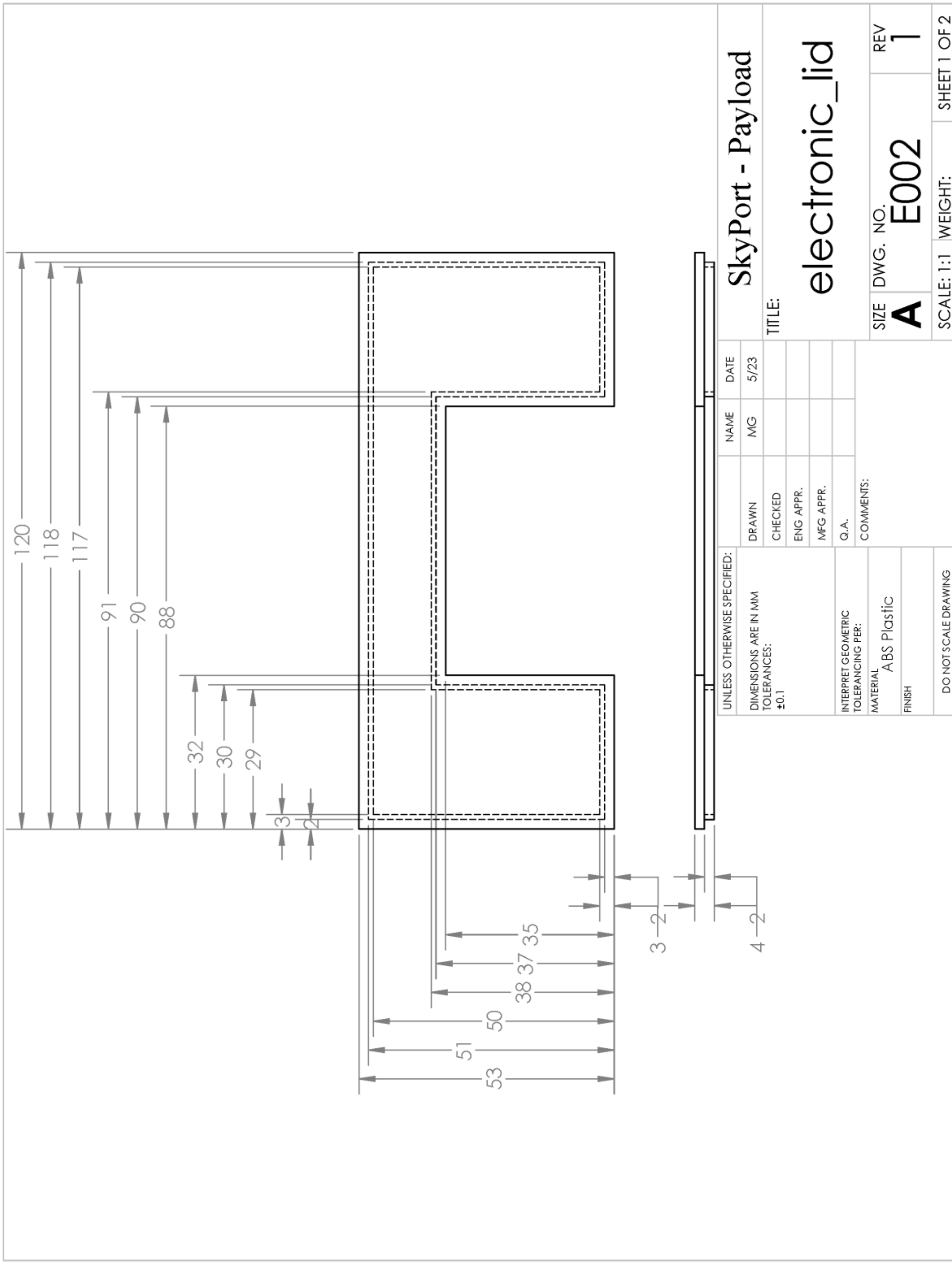
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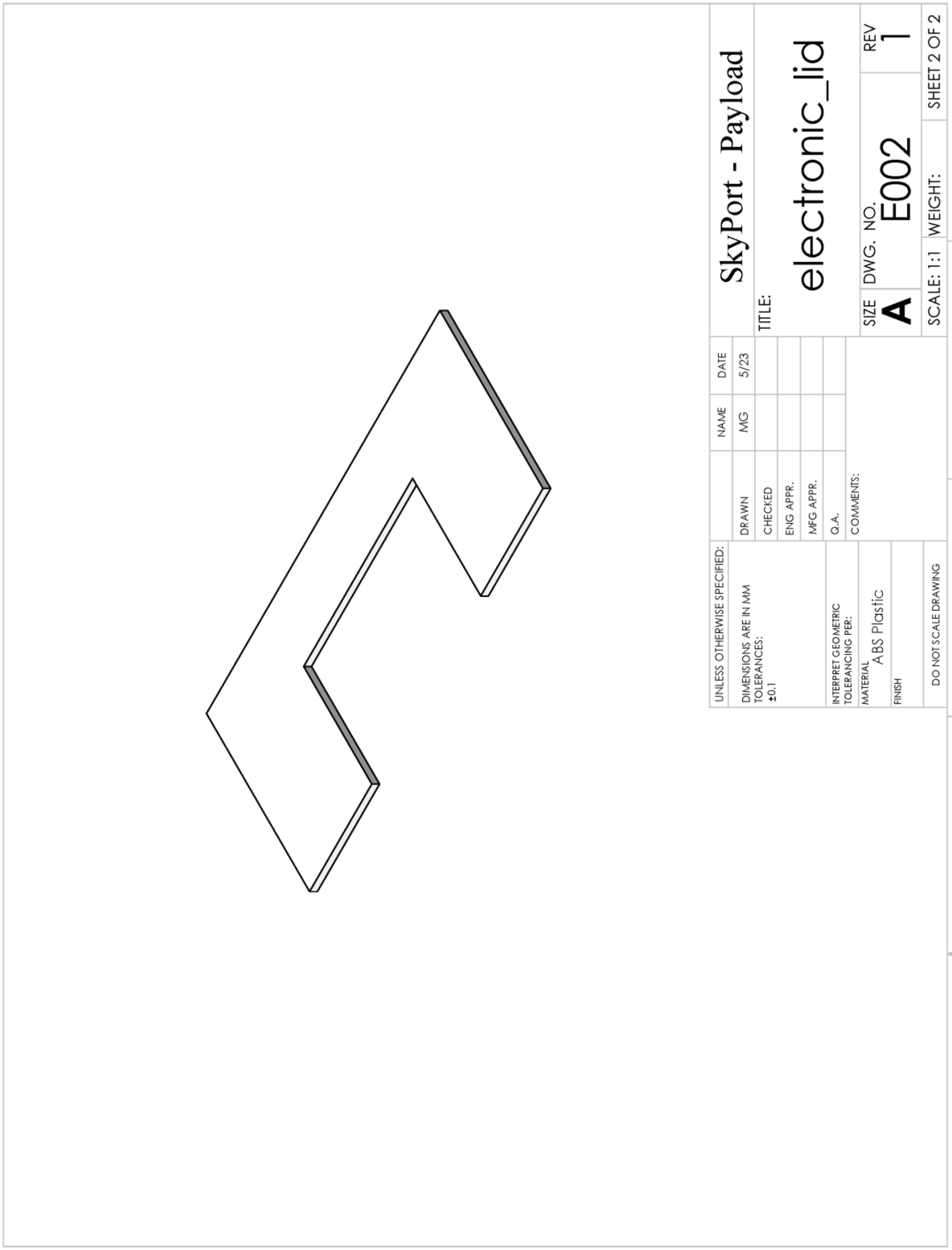
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## Appendix D – Thermal FEA Simulation Figures

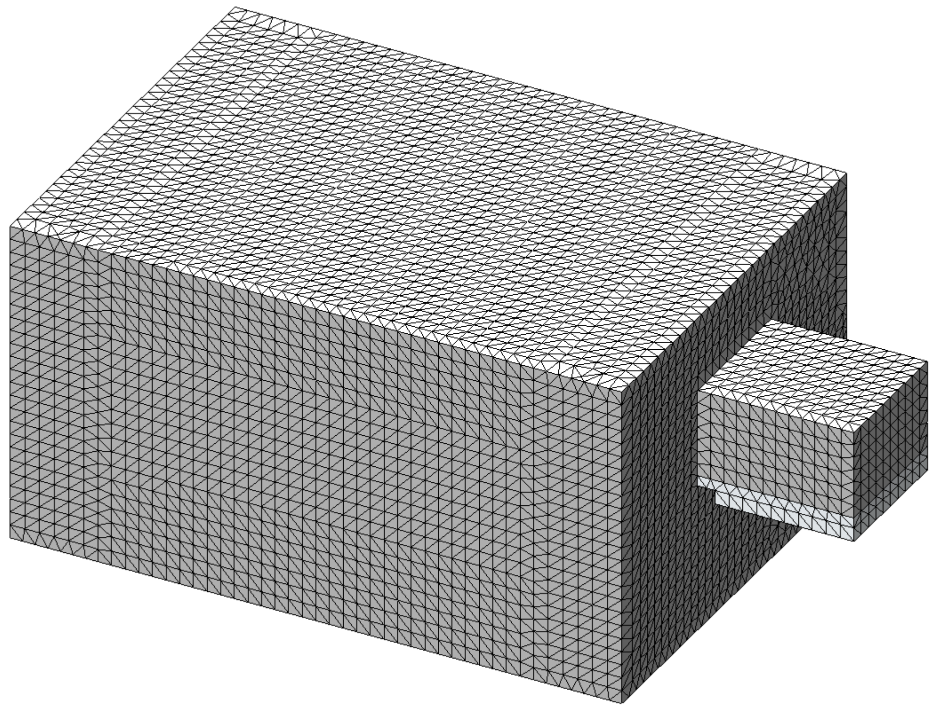


***Figure D.1:*** Mesh diagram of the simplified model with triangle density.

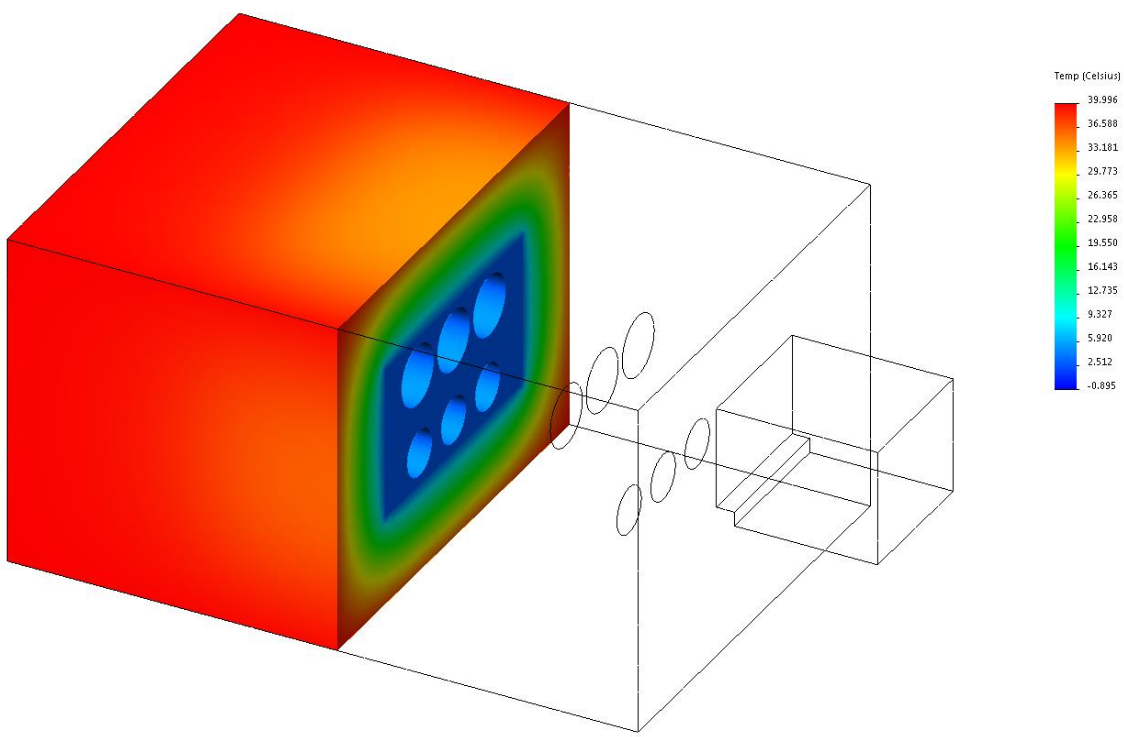



***Figure D.2:*** Trimetric cross-section of thermal plot. Temperature ranges from 0 °C (blue) to 40 °C (red).

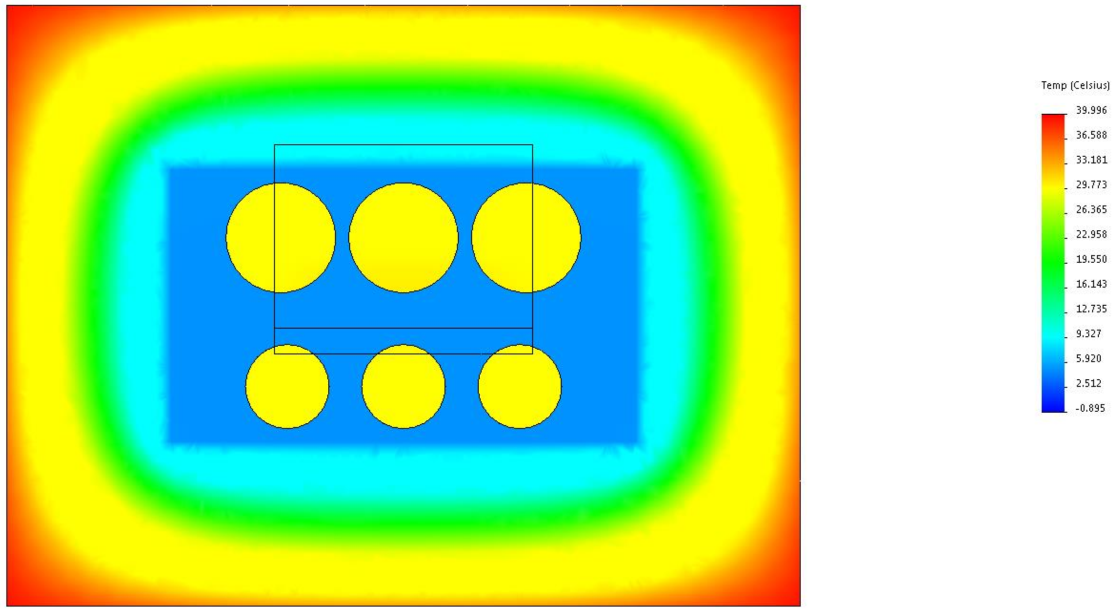



***Figure D.3:*** Front cross-section of thermal plot. Temperature ranges from 0 °C (blue) to 40 °C (red).

# Appendix E – Experimental Results

## *E.1 Fan and Heat Sink Data*

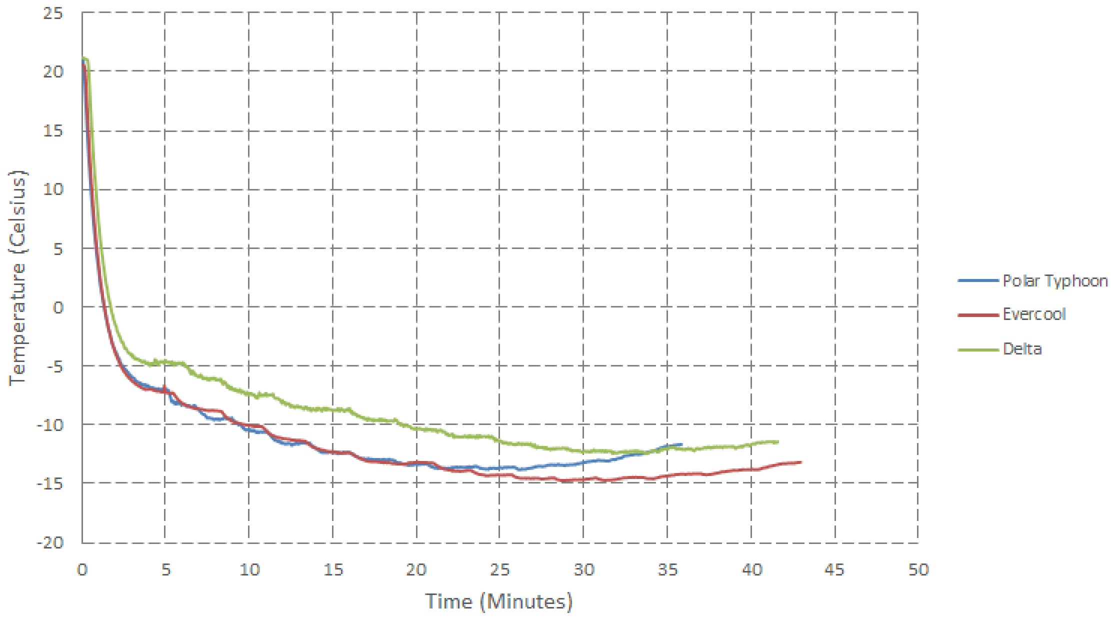



***Figure E.1:*** TEM temperature due to heat dissipation effects using the black 50 mm heat sink.

## *E.2 Thermoelectric Module Data*

***Table E.1:*** Optimal current test results for the Marlow RC12-8-01LS.

| Current (A) | Voltage (V) | Power (W) | TEM Temp (°C) | Chamber Temp (°C) | Ambient Temp (°C) | Temp Diff. (°C) |
|---|---|---|---|---|---|---|
| 1.5 | 3.9 | 5.85 | 2.05 | 2.97 | 22.3 | 19.33 |
| 1.75 | 4.5 | 7.88 | 0.28 | 1.38 | 22.3 | 20.92 |
| 2.0 | 5.0 | 10.0 | -2.04 | -0.88 | 22.2 | 23.08 |
| 2.1 | 5.2 | 10.92 | -2.85 | -1.64 | 22.4 | 24.04 |
| 2.2 | 5.5 | 12.1 | -3.33 | -2.05 | 22.4 | 24.45 |
| 2.3 | 5.7 | 13.11 | -3.96 | -2.63 | 22.2 | 24.83 |
| 2.4 | 5.9 | 14.16 | -4.47 | -3.14 | 22.4 | 25.54 |
| 2.5 | 6.2 | 15.5 | -4.90 | -3.49 | 22.2 | 25.69 |
| 2.6 | 6.4 | 16.64 | -5.91 | -4.49 | 22.1 | 26.59 |
| 2.65 | 6.5 | 17.23 | -6.24 | -4.86 | 21.9 | 26.76 |

***Table E.2:*** Optimal Current test results for the Marlow TG12-6L.

| Current (A) | Voltage (V) | Power (W) | TEM Temp (°C) | Chamber Temp (°C) | Ambient Temp (°C) | Temp Diff. (°C) |
|---|---|---|---|---|---|---|
| 1.5 | 4.9 | 7.35 | -1.61 | -0.47 | 22.7 | 23.17 |
| 1.75 | 5.65 | 9.89 | -3.89 | -2.63 | 22.2 | 24.83 |
| 2.0 | 6.4 | 12.8 | -5.50 | -4.10 | 22.1 | 26.20 |
| 2.1 | 6.8 | 14.28 | -5.85 | -4.39 | 22.4 | 26.79 |
| 2.2 | 7.1 | 15.62 | -6.21 | -4.69 | 22.2 | 26.89 |
| 2.3 | 7.35 | 16.91 | -6.48 | -4.89 | 22.2 | 27.09 |
| 2.4 | 7.7 | 18.48 | -6.85 | -5.17 | 22.3 | 27.47 |
| 2.5 | 8.0 | 20.0 | -6.90 | -5.19 | 22.3 | 27.49 |

***Table E.3:*** Optimal Current test results for the Laird CP,2,31,10.

| Current (A) | Voltage (V) | Power (W) | TEM Temp (°C) | Chamber Temp (°C) | Ambient Temp (°C) | Temp Diff. (°C) |
|---|---|---|---|---|---|---|
| 4.5 | 1.95 | 8.775 | -6.82 | -6.39 | 22.1 | 28.49 |
| 5.0 | 2.15 | 10.75 | -8.45 | -8.01 | 22 | 30.01 |
| 5.5 | 2.36 | 12.98 | -8.47 | -8.02 | 21.9 | 29.92 |
| 5.6 | 2.41 | 13.50 | -8.51 | -7.95 | 22 | 29.95 |
| 5.7 | 2.48 | 14.14 | -8.53 | -7.97 | 22.1 | 30.07 |
| 5.8 | 2.5 | 14.5 | -8.67 | -8.07 | 21.9 | 29.97 |
| 5.9 | 2.54 | 14.99 | -8.62 | -8.0 | 22 | 30 |
| 6.0 | 2.59 | 15.54 | -8.50 | -7.8 | 22 | 29.8 |

***Table E.4:*** Optimal Current test results for the Laird CP,2,71,10.

| Current (A) | Voltage (V) | Power (W) | TEM Temp (°C) | Chamber Temp (°C) | Ambient Temp (°C) | Temp Diff. (°C) |
|---|---|---|---|---|---|---|
| 2.5 | 2.77 | 6.93 | 0.29 | 0.05 | 22.95 | 22.9 |
| 3.0 | 3.27 | 9.81 | -1.7 | -1.83 | 22.7 | 24.53 |
| 3.5 | 3.74 | 13.09 | -2.57 | -2.58 | 22.6 | 25.18 |
| 3.7 | 3.97 | 14.69 | -5.68 | -5.76 | 22 | 27.76 |
| 4.0 | 4.27 | 17.08 | -6.27 | -6.34 | 21.34 | 27.68 |
| 4.3 | 4.56 | 19.61 | -6.54 | -6.57 | 21.35 | 27.92 |
| 4.4 | 4.66 | 20.50 | -6.47 | -6.49 | 21.4 | 27.89 |

## *E.3 Battery Configuration Data*

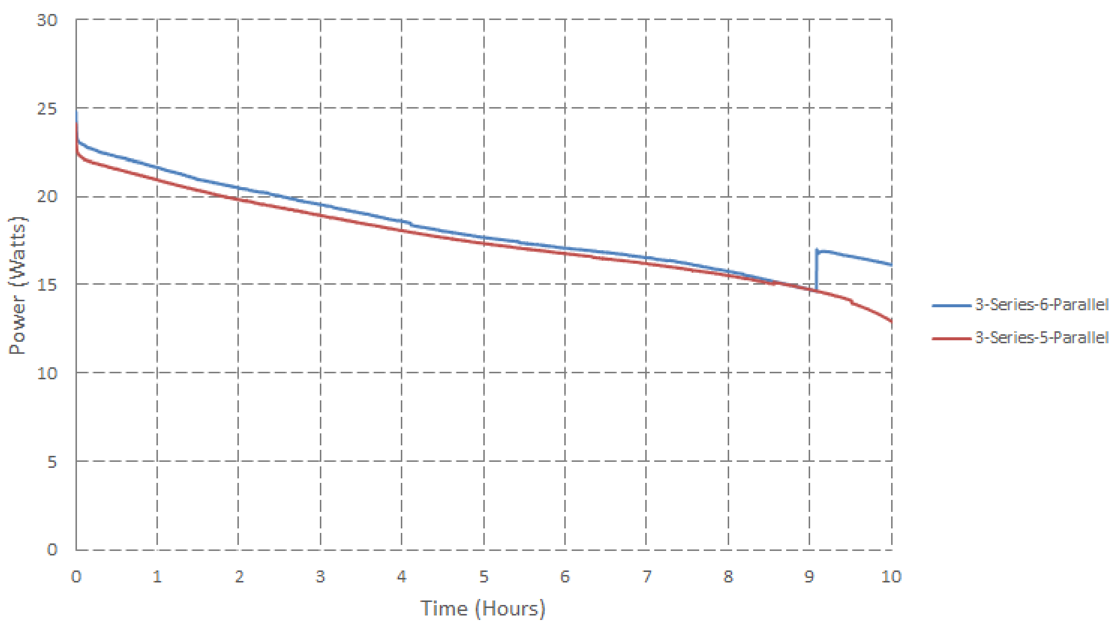



***Figure E.2:*** Power discharge comparison for different battery configurations.

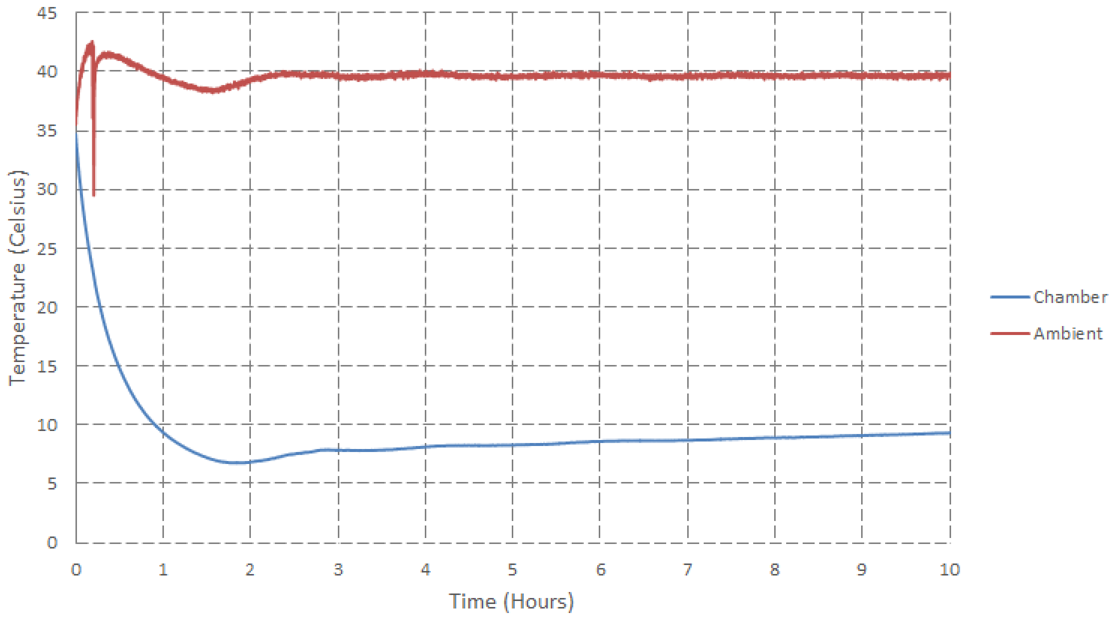



***Figure E.3:*** Temperature monitoring with the payload inside an incubator, using the battery pack.

## *E.4 Temperature Control Testing Data*

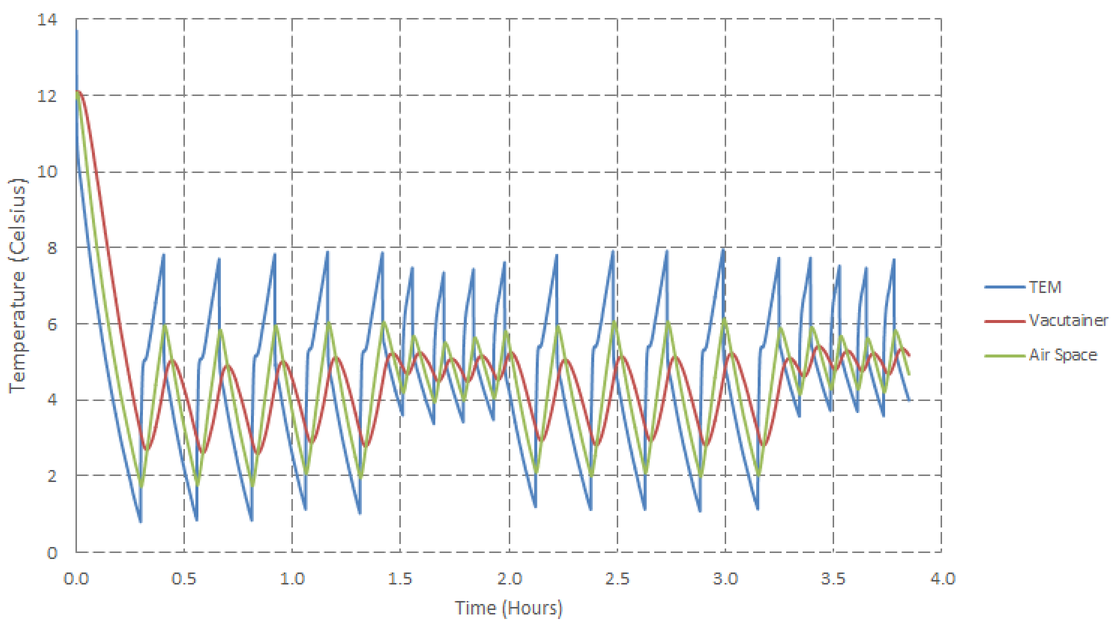



***Figure E.4:*** Payload temperature comparisons during the feedforward loop test.

## Appendix F – Patent

Santa Clara University

**Invention Disclosure Form**

Office of Research Initiatives
Santa Clara University
500 El Camino Real
Santa Clara, CA 95053
(408) 551-1817 phone
(408) 551-1873 fax

Santa Clara University is committed to supporting the development of new technologies. *Faculty Handbook* section 3.7.5 describes the University policy on patents including the distribution of royalties. The patent policy of the University applies to all potentially patentable discoveries or inventions conceived or first reduced to practice by anyone using University funds, material, or facilities. In particular, the University patent policy is defined in terms of three categories of inventions:

Category 1. *Discoveries or inventions that are subject to the terms of sponsored projects or other agreements between the University and a third party*. These inventions shall be disposed of in accordance with the terms of the applicable agreement. Most agreements provide that the University will take title to inventions and will grant certain license rights to the sponsor.

Category 2. *Discoveries or inventions that involve the significant use of funds, materials, or facilities administered by the University but that do not involve University obligations to a third party*. These inventions shall be the property of the University. Significant use occurs when the University provides resources above and beyond those that would be routinely available to the inventor as a direct result of his or her affiliation with the University.

Category 3. *Discoveries or inventions that do not involve either University obligations to a third party or the significant use of funds, materials, or facilities administered by the University*. These inventions shall be the property of the inventor.

Furthermore, under the University patent policy, any discovery or invention conceived or first reduced to practice by anyone using University funds, material, or facilities must be disclosed promptly to the University by means of this Disclosure Form except for discoveries or inventions in which the inventor has sole ownership rights. The University has contracted with the Stanford Office of Technology Licensing to evaluate disclosures and manage patent procedures for inventions that shall be the property of the University. The patent process is coordinated by the Associate Provost for Research Initiatives and involves the following steps:

1. Complete this disclosure form.
2. Submit the completed, signed hard copy of the form to the Associate Provost for Research Initiatives.
3. Upon receipt, the Associate Provost will contact the Stanford Office of Technology Licensing to formally initiate the disclosure evaluation process.

4. The inventor can expect to be contacted by a representative of the Stanford Office of Technology Licensing to evaluate the disclosure and start the process of determining if the invention meets the criteria for pursuing a patent.
5. Any questions regarding the process should be directed to the Associate Provost for Research Initiatives (ashachter@scu.edu).

***An invention and technology disclosure is a legally important document that describes what is invented and the circumstances under which the invention was made or the technology created. Please complete the disclosure form carefully.***

**1. Title of the invention or technology**

Feedforward Temperature Control for a Thermoelectric Cooler

**2. Description of the invention or technology**
**2a. General purpose of the invention and what problem it solves.**

Access to basic health care is a major persisting problem around the globe, especially in rural parts of the world. One of the many facets of this problem is access to vaccine treatment. The transportation and storage of vaccines is an issue that is still being solved and improved upon today. One of the common solutions to this problem is the use of passive coolers such as ice packs and other refrigerants. The potential issue with passive cooling is that the temperature cannot be actively controlled. This is evident, as many vaccines are wasted due to incorrect storage temperature. The invention discussed in this document utilizes an active cooling system with thermoelectric modules that accomplishes two tasks. It maintains vaccines and blood samples at the proper storage temperature range of 2-8 °C while reducing power consumption. This is accomplished using a feedforward control loop. In order to save power, two operating modes are utilized based on both the ambient temperature and the chamber temperature.

**2b. Technical description of the invention including a discussion of features believed to be new and advantages over existing methods, devices or materials, and a description of unique and non-obvious aspects of the invention. For software, describe any novel algorithms. For a database, describe novel features of the structure. Attach photos, drawings or other technical data/material as appropriate.**

The main subsystems that the device is comprised of are as follows: Heat Removal, Outer Insulation, Temperature Control, and Power Supply. These subsystems serve as a breakdown of components with similar functions in close proximity to each other. Components in the Heat Removal Subsystem include a thermoelectric module (TEM), planar heat pipe, heat sink, fan, and the aluminum inner chamber. The Outer Insulation Subsystem consists primarily of expanded polystyrene foam and birch plywood panels. The Temperature Control Subsystem consists of an Arduino microcontroller, buck converters, relays, and temperature sensors in a 3D printed enclosure. The Power Supply Subsystem consists of several lithium-ion battery cells, also housed in a 3D printed enclosure.

Since there is a high percentage of wasted vaccines due to incorrect storage temperatures with passive cooling systems, active cooling with a TEM is a valid solution. By using active cooling, the temperature of the inner chamber is precisely controlled. There are several active cooling systems that can be used to keep the vaccines cool at their acceptable temperature. Two of these devices are the TEM and the compressor-based system. For our active cooling device, a TEM pumps heat out from the inner chamber to the environment. Since TEMs are traditionally known to be inefficient, we required a good heat dissipation system and a highly resistive insulator.

The vaccines are placed inside an aluminum enclosure to keep the vaccines in place. Due to the high thermal conductivity of the aluminum, it allows it to transfer the cold from the TEM to the vaccines at a faster rate, maintaining a uniform temperature gradient. In order to ensure good contact between the aluminum and the heat pipe, thermal interface material was used. This material improves the thermal conductivity between the aluminum as long as the pieces of aluminum are securely fastened. The expanded polystyrene foam (EPS) is used as the main insulator and to enclose the vaccines because it is lightweight, impact resistant, and has low thermal conductivity. The TEM pulls heat from the inner chamber through the heat pipe, and this heat is then dissipated into the environment with the fan and heat sink. The basic operating principle of the device design is shown below in *Figure 1*.

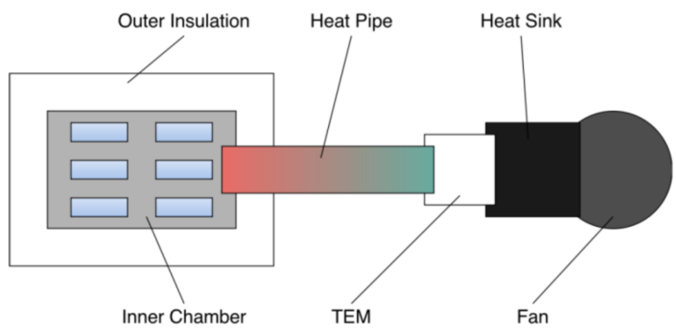



***Figure 1:*** Basic schematic detailing the flow of heat from left to right.

**Key Components:**

*Thermoelectric Module*

This active cooling device operates on the principle known as the Peltier effect, in which a temperature gradient is created between each side, induced by an applied electrical current. A characteristic of TEMs is that temperature is proportional to current. As shown in *Figure 2*, TEMs consist of two ceramic plates with alternating semiconductor material in between. The plates serve as thermally conductive junctions, known commonly as the “hot side” and “cold side”. The flow of electrons through the TEM also permits the flow of heat, in a process known as joule heating. This creates a temperature difference in which heat is absorbed through the “cold side” and rejected out of the “hot side”. The following diagram shows the basic operating principle.

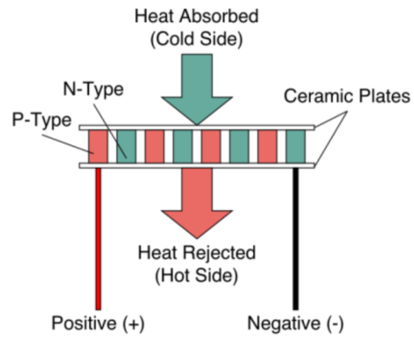



***Figure 2:*** Operating principle of a thermoelectric module.

Compared to other active cooling systems, such as vapor-compression systems normally found in refrigerators, TEMs are not especially efficient in terms of the coefficient of performance (COP), the ratio of heat removed to the required work. This is due mainly to the negative effects of joule heating. The equation shown below models the heat absorbed into the TEM, expressed as $Q_C$.

$$Q_C = SIT_C - K(T_H - T_C) - \frac{1}{2}I^2R$$

The first term in this equation represents the Peltier effect. The second term represents the resistivity of the TEM due to conduction (an inherent property of the TEM) and the third term represents joule heating. Increasing the amount of current eventually causes the third term to dominate, reducing the cooling and lowering the COP. With regard to the application in the device, supplying too much current will reduce the temperature difference the TEM can achieve.

*Heat dissipation*

The heat sink and fan work in tandem to improve the performance of the TEM. The heat sink conducts the rejected heat from the TEM hot side through the fins. These fins increase surface area while maintaining the cross-section, increasing the effectiveness of the fan's forced convection. The fan intake and two exhaust channels are exposed on the bottom of the device so that ambient air can travel through the system. A cross-section of this ventilation illustrating the airflow is shown below in *Figure 3*.

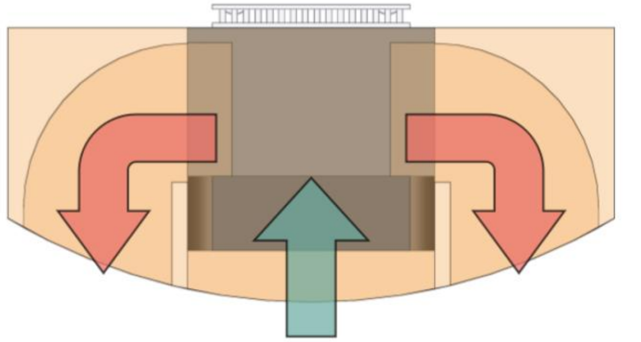


***Figure 3:*** Cross-section of the ventilation.

*Inner Chamber*

The inner chamber of the device is made up of two 6061 aluminum blocks machined using a vertical mill. These blocks have three holes each, sized to fit vaccine vials in one and blood sample vacutainers in the other. Aluminum has a high thermal conductivity, allowing for a uniform temperature gradient throughout the material and an effective removal of heat. Using aluminum as the medium for conductive heat transfer allows the Heat Removal Subsystem components to work together effectively. For ease of manufacturing, the blocks are machined as two separate pieces. Once joined together, there is high potential for air pockets between the machined faces. To improve the thermal conductivity between the two blocks, thermal interface material is used. This putty-like material is in the form of a thin sheet, and possesses a thermal conductivity greater than air.

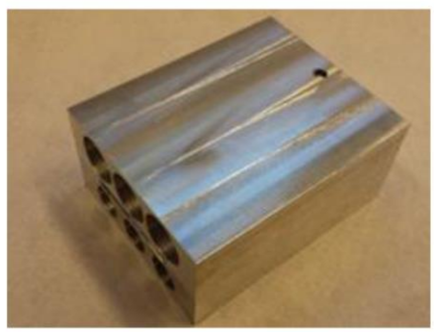


***Figure 4:*** Aluminum chamber

*Planar Heat Pipe*

The performance of the TEM depends on the effectiveness of insulation and heat dissipation components, both of which take up physical space. In order to maintain a small device cross-section while accommodating these components, the design utilizes a planar heat pipe. This component relocates the transfer of heat from the inner chamber to the TEM such that neither the insulation nor heat dissipation is compromised. Additionally, the heat pipe allows for greater distance between the inner chamber and the TEM, decreasing the potential for heat to cycle back into the subsystem.

Heat pipes are heat transfer devices used in laptops and televisions that operate on two principles: thermal conduction and phase transition. The working fluid inside the heat pipe condenses as it travels from the inner chamber end to the TEM end and evaporates as it travels back to the inner chamber end. Heat pipes are effective heat transfer components due to the high thermal conductivity that boiling and condensing points possess. The heat pipe used in the design has an effective thermal conductivity of approximately 3000 W/m·K. The functionality of the planar heat pipe is shown below in *Figure 5*, where heat is transferred from the red end to the blue end.

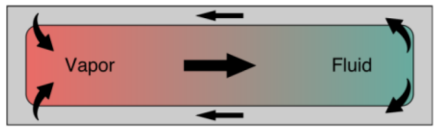



***Figure 5:*** Heat pipe diagram.

*Insulation*

The Outer Insulation Subsystem protects the inner chamber from the ambient temperatures that can exceed 40 °C. This subsystem is constructed using expanded polystyrene (EPS) foam because it has a high thermal resistivity in addition to being lightweight.

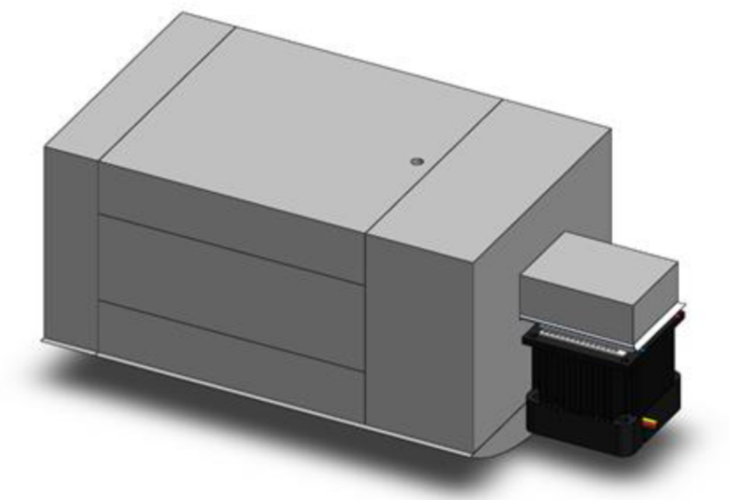


***Figure 6:*** Outer design of the device

*Temperature Controller*

The Temperature Control Subsystem regulates the power delivered to the TEM, ensuring that the inner chamber is maintained within the correct temperature range. This is achieved using a feedforward control loop. The feedforward loop switches between two modes, Full Power Mode and Power Saving Mode, depending on the ambient temperature. Full Power Mode is based on the optimal current value for a 32 °C temperature difference, and Power Saving Mode is based on the power required to maintain a 20 °C temperature difference (28 °C ambient temperature and internal temperature of 8 °C). When the ambient temperature is detected to be greater than 28 °C, Full Power Mode is activated. Otherwise, Power Saving Mode is activated. In addition to the ambient temperature, the feedforward loop is also influenced by the temperature of the inner chamber. If the temperature of the inner chamber falls to 4 °C, the power is turned completely off. When the inner chamber temperature is above 6 °C, the power is turned on depending on the ambient temperature. The feedforward loop results in a slight temperature oscillation inside the inner chamber that is within the 2-8 °C range due to the power-saving on-off characteristic. It also saves power by switching between two different operating powers.

**Unique Features:**

*Claim 1: Feedforward Loop and its Circuitry*

Most control systems are based on a feedback control loop or model predictive control. Both of these control loops can be complex due to the nature of the dynamic systems they are often implemented in. One of the most common control loops is the proportional-integral-derivative (PID) controller. This controller relies on current, past, and anticipated error to adjust the system. The device does not use a PID controller to regulate the power because this process requires too much time to correct the temperature, shown below in *Figure 7*.

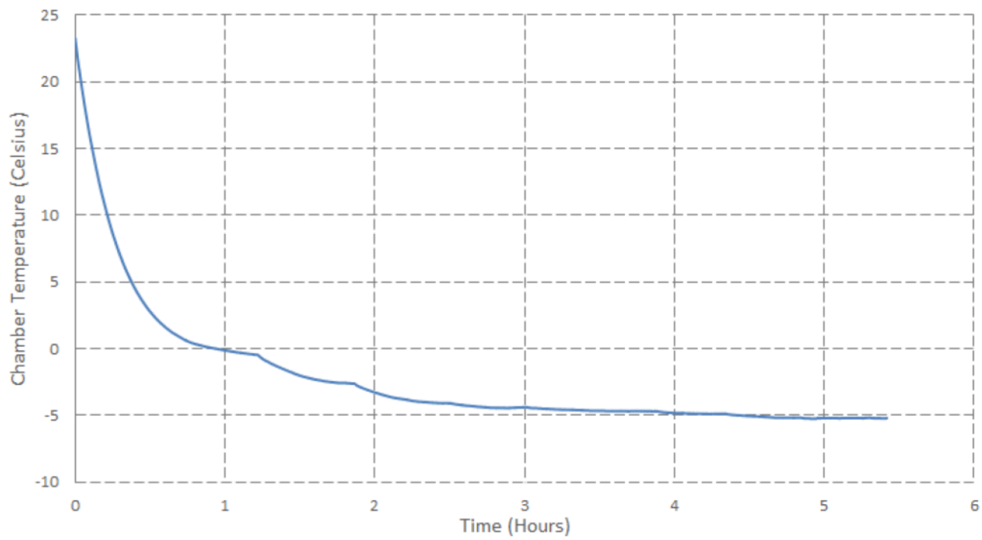



***Figure 7:*** TEM testing shows how long it takes to reach steady-state temperature.

Instead, a very basic feedforward loop uses the temperatures of the environment and inner chamber to switch between two operation modes. From *Figure 7*, it is important to note the time that it takes the TEM to reach a steady state temperature. For this TEM model, it took almost 40 minutes to reach a steady-state temperature when the current was increased from 1.5 A to 1.75 A, and an additional 40 minutes from 1.75 A to 2 A. This behavior is the main reason why a feedforward control loop was utilized instead of a PID controller.

The temperature controller utilizes an Arduino microcontroller, two buck converters, two relays, and two temperature sensors. The adjustable DROK® buck converters step down the power from the single Power Supply Subsystem source for each operating mode. One buck converter adjusts the voltage to 12 V for Full Power Mode. The Arduino Micro is also powered from this output. The other buck converter adjusts the voltage to 8 V based on TEM test results. Both of these powers are connected to the TEM with AZ830 relays in between. These are used as on-off switches controlled by the Arduino based on the TMP 36 temperature sensor readings. One sensor is exposed to the ambient environment and the other is exposed to the air inside the inner chamber. A schematic of the components and their interaction in the control system is shown below in *Figure 9*.

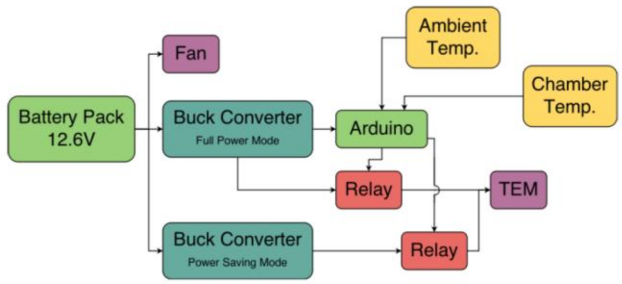



***Figure 9:*** Temperature sensing and power control

*Claim 2: The use of latches to close the device, ensuring a tight fit.*

The insulation of the chamber where the vaccines are going to be kept is important to ensure a more efficient heat removal system. The chamber should be like a vacuum to prevent air convection. By preventing air convection the TEM will have to perform less work to be able to remove heat, and the heat transfer from the inside of the device to the ambient temperature will be reduced if the chamber has a tight seal. Therefore, using latches to seal the device allows for a device that will prevent any air convection from affecting the system. The placement of these latches is shown below in *Figure 10*.

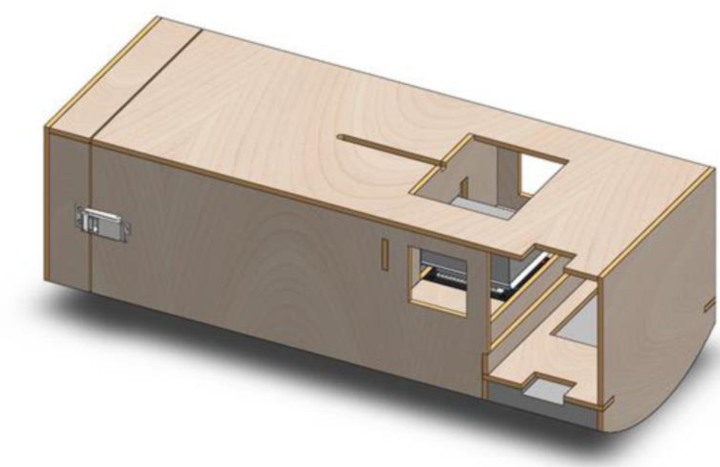
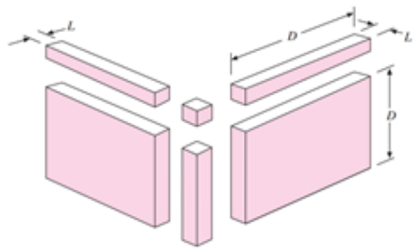


***Figure 10:*** Latch placement on device to ensure a tight seal.

*Claim 3: Insulation Thickness*

The Outer Insulation Subsystem protects the inner chamber from the ambient temperatures that can exceed 40 °C. This subsystem is constructed using expanded polystyrene (EPS) foam because it has a high thermal resistivity in addition to being lightweight. The EPS foam is cut into panels manually using a hot wire foam cutter. The panels are bonded with Loctite PL Premium Polyurethane Construction Adhesive. The dimensions for the EPS foam were determined based off of 3D shape factor calculations. Using the known properties of the EPS foam and the desired temperature difference between the walls, we determined that a wall thickness of 1 inch would require just under 2 W of cooling. The following figure and equations show how the optimum thickness of 1 inch for the Styrofoam was determined.




Source: Holman, J. P. *Heat Transfer*. Boston, MA: McGraw Hill Higher Education, 2010.

***Figure 11:*** 3D Shape Factor Calculations

$$Q = kS\Delta T$$

The above equation shows the heat loss based on the shape factor, S. There are three different shape factors that need to be calculated for the walls, edges, and corners.

$$S_{wall} = \frac{A}{L}$$

$$S_{edge} = 0.54D$$

$$S_{corner} = 0.15L$$

Using these equations the cooling power required to achieve a 38 °C temperature difference is 1.935 W.

**2c. Possible variations and modifications to the invention as well as products or processes that could result from the invention.**

There are a number of modifications that can be implement to the invention to improve the user interface:

- Printed circuit board (PCB) integrate electrical components
    - A PCB can be created to minimize the space required for the electronic components. The PCB will also allow for the development of desired voltage boost/buck converters.
- LCD Display
    - Adding a LCD display to the device will allow the user to know the exact temperature of the device at all times, and notify the user of any system failures.
- Customized TEM
    - The TEMs that were tested and used on the device were consumer models. In order to make the system more efficient, a custom TEM could be designed.
- Application for Anything
    - The device was initially designed to carry vaccines and be used for aerial transport. However, the chamber can be modified to fit any thing that needs to be cooled, and it can be used for any type of transportation.

**2d. Competing technologies including current solutions for the same problem, how and how much better the invention is relative to competing technologies, listing of related technical papers or patents for similar technology, a description of degree of research in the field:**

*Source:*
U.S. patent application Ser. No.US 20140352329 A1, entitled TEMPERATURE-STABILIZED STORAGE SYSTEMS WITH REGULATED COOLING , naming Jonathan Bloedow; Ryan Calderon; David Gasperino; William Gates; Roderick A. Hyde; Edward K.Y. Jung; Shieng Liu; Nathan P. Myhrvold; Nathan John Pegram; Clarence T. Tegreene; Charles Whitmer; Lowell L. Wood; JR.; and Ozgur Emek Yildirim as inventors, filed 31 May 2013, is related to the present application.

https://www.google.com/patents/US20140352329?dq=thermoelectric+vaccine+cooler&hl=en&sa=X&ei=7sVaVZvAIMbVoASgkYOwBg&ved=0CDIQ6AEwAw

*Summary:*
This product addresses the same issue as our design, also utilizing a thermoelectric unit that consists of a cooling region, adiabatic region, a lid region, and an electronics unit attached to the lid region. The thermoelectric unit is in contact with the second end of the thermal heat pipe, and a thermal dissipator unit in contact with the thermoelectric unit. The cooling region includes an outer wall with an inner surface and an outer surface, a temperature sensor positioned adjacent to the outer surface of the outer wall, and a first region of thermal heat pipe positioned within the outer wall substantially parallel to the inner surface, and the first region of the thermal heat pipe including a first end with a heat absorbing interface.

*Key Differences:*

1. Thermal heat pipe
    a. SCU: Planar heat pipe
    b. Bloedow, et. al: Tubular cross section
2. Method of cooling
    a. SCU: Active cooling by using TEM
    b. Bloedow, et. al: Active and passive cooling by using a thermoelectric unit and phase change material

*Source:*
U.S. patent application Ser. No.WO2003040740, entitled FEEDFORWARD TEMPERATURE CONTROL OF DEVICE UNDER TEST, naming Touzelbaev Maxat as inventor, filed 18 October 2002, is related to the present application.

https://www.google.com/patents/WO2003040740A2?cl=en&dq=feedforward+temperature+control&hl=en&sa=X&ei=4M9lVaKJPIGWsQWOsoHABA&sqi=2&pjf=1&ved=0CB0Q6AEwAA

*Summary:*
This invention consists of a feedforward temperature controller that changes the power level of a semiconductor device when it experiences a change in temperature. The temperature controller, or thermal head, consists of power levels that are selected for use during electrical testing sequence, based on the characterization of the temperature change of the device under test in response the electrical testing sequence, so that the device under test remains at a constant temperature during the electrical testing sequence. Our temperature control works on the same principle by changing the power supplied to the TEM to maintain a constant temperature in the inner chamber based on changes in the ambient temperature.

*Key Differences:*

1. Power control
    a. SCU: Varying the voltage supplied to the TEM
    b. Touzelbaev: Varying the current supplied to the semiconductor
2. Power supply
    a. SCU: Lithium-ion cells power the TEM where the voltage is controlled by voltage regulators
    b. Touzelbaev: A function generator changes the current supplied to the semiconductor
3. Temperature sensor
    a. SCU: TMP 36
    b. Touzelbaev: A temperature sensitive diode
4. Electrical components
    a. SCU: Voltage regulators, power switches, microcontroller, temperature sensor
    b. Touzelbaev: Thermal head and temperature sensitive diode

*Source:*
U.S. patent application Ser. No.US 8353167 B2, entitled SOLAR-POWERED REFRIGERATED CONTAINER, naming Ryan McGann as inventor, filed 16 Apr. 2008, is related to the present application.

*Summary:*
The portable refrigerator unit has the ability to keep food, beverages, and other desired objects cool despite the conditions that may exist outside the container. This cooling unit uses active cooling with a TEM powered by a solar panel, where a rechargeable battery can assist during periods of inadequate solar power generation. The refrigerator container employs a system that uses heat sinks, fans, and vents that maintains an insulated environment within the container that is up to 40 °C below the ambient temperature.

*Key Differences:*
1. Power supply
    a. SCU: Lithium-ion cells that power the TEM, temperature controller, and fan
    b. McGann: Solar collector that has been electrically coupled to recharge the batteries and a generator that has been coupled to the wheels and configured to also recharge the batteries
2. Heat dissipation
    a. SCU: The use of an external heat sink and fan that is coupled with the TEM
    b. McGann: Internal heat sink and fan secured to the cavity and the external heat sink and fan secured to the thermoelectric cooling unit
3. Temperature difference
    a. SCU: 32 °C
    b. McGann: 40 °C
4. Battery Life
    a. SCU: Lithium-ion cells are able to power device for 10 hours
    b. McGann: Batteries without the assistance of solar panel can power the container for up to 3 to 4 hours

*Source:* U.S. patent application Ser. No. US6308518 B1, entitled THERMAL BARRIER ENCLOSURE SYSTEM, naming Rick C. Hunter as inventor, filed 28 September 2000, is related to the present application.

https://www.google.com/patents/US6308518?dq=portable+vaccine+carrier+box+employing+thermoelectric+module&hl=en&sa=X&ei=uvNlVdSqMY3XoASGjoGYDQ&ved=0CB0Q6AEwAA

*Summary:*
This products combines active and passive cooling to cool an energy storage material and insulate the material when the cooling source is removed. The thermal barrier enclosure system consists of a temperature controller, active heat pump, a temperature sensitive device, a thermal conduit through which energy flows, and a thermal barrier. This product can achieve tight tolerance temperature control even when the external temperature may be above or below the control volume temperature.

*Key Differences:*

1. Method of cooling
    a. SCU: TEM
    b. Hunter: Thermal barriers that consist of phase change material and a heat pump
2. Power supply
    a. SCU: Lithium ion cells that power the TEM, temperature controller, and fan
    b. Hunter: Power source (not specified) will power heat pump and microcontroller
3. Temperature controller
    a. SCU: The use of voltage regulators that are controlled by a microcontroller that control the temperature range in the device inner chamber
    b. Hunter: A thermal actuator that opens the thermal conduit to cause or inhibit the flow of thermal energy to control the temperature range in the device control volume

*Source:*

D. Astrain, A. Martinez, J. Gorraiz, A. Rodriguez, and G. Perez
"Computational Study on Temperature Control Systems for Thermoelectric Refrigerators", Journal of Electronic Materials, 41, 1081, 2012
DOI: 10.1007/s11664-012-2002-0

*Summary:*

This study on temperature control systems for TEMs explores the inefficiency of on-off switches used as the main control system. The problem is that once the refrigerator reaches the lower temperature limit, the TEM turns off, resulting in the heat stored in the heat exchanger to go back into the refrigerator. In order to solve this problem, the TEM is supplied with a minimum voltage instead of turning the TEM completely off.

*Key Differences:*

1. On-Off Switch
    a. SCU: The TEM is completely turned off once the chamber reaches the lower temperature limit
    b. Astrain: The TEM is not completely turned off once the refrigerator reaches the lower temperature limit

**2e. Stage of development including current state of research and steps to commercialization:**

The current design maintains the inner chamber temperature at 5 °C for at least 10 hours. Because the ambient temperature affects the performance of the heat removal system, the device utilizes a feedforward loop with two operating modes: Full Power Mode and Power Saving Mode. These two modes help save power while still maintaining the desired temperature. The device also saves power because the TEM is not constantly operating, a result of the on-off characteristic of the control system.

This fully-functioning prototype can be optimized for commercialization by altering design characteristics and manufacturing processes that will not have a negative impact on functionality. These aspects will improve manufacturing and assembly, maintenance, user interface, and also reduce costs and material waste. This includes the design of a printed circuit board for the electronics, changing the inner chamber fabrication from milling to extrusion, and changing the material of the outer shell so that it can be manufactured in less separate pieces.

The design can also be improved by developing customized components such as the TEM, heat sink, relay, and power converter. With additional research, design specifications for a more effective TEM and heat sink can be determined and submitted for fabrication. To improve the temperature control system, customized relays and power converters can be implemented. With additional testing and implementation, accurate power values for each operation mode can be used as the basis for designing these components.

**2f. Commercialization possibilities:**

This device can be commercialized in at least two ways. One possibility is to license the device to health organizations that specialize in vaccine delivery, such as Gavi and UNICEF. This can include the World Health Organization, in which our device could be used to influence vaccine carrier requirements and regulations. A second commercialization possibility involves a reapplication of the device for items such as perishable foods. While this application would still be implemented on a small scale, additional research can facilitate improvements such as increased storage volume.

**3. Inventors or developers** (provide the following for ***all*** presumed inventors or developers; use an additional disclosure form if there are more than three inventors)

**Total number of inventors: 4**

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**Citizenship**: USA

**4. Obligations to third parties (attach any inventions sections of third party agreements)**
**4a. What funds supported the work leading to this invention? Please list all sources of funding for the invention (include any federal, non-federal, foundation, and industry funding, gifts, Santa Clara University funds, etc.). For non-SCU funds include: contract/grant number, sponsor, and PI(s).**

No obligation financial support from the Willem P. Roelandts and Maria Constantino-Roelandts Grant Program ($1600) and from the Santa Clara University School of Engineering ($1500).

**4b. Are you a party to any other agreement(s) pertaining to the invention (e.g. material transfer agreement, collaboration, patent agreement with any other entity)?**

☐ **yes** ☒ **no**

**If yes, please list third party names and types of agreements:**
**None**

**5. History of invention or technology**
**5a. Date of initial idea: 9/23/14**

**5b. Date of conception (when all the essential elements of an invention were formed in the inventor's mind): 2/1/15**

**5c. Date first reduced to practice (first successful demonstration of the invention): 5/14/15**

**5d. Date and venue of first public disclosure (date and venue of proposal or manuscript submission, date and venue of conference presentation, date and venue of electronic or web postings): 5/14/15**

**5e. Date and venue of any future public disclosures (date and venue of future, planned publications, conference presentations, etc.): N/A**

**6. Rights and royalties (*__all__* inventors must sign; please use another disclosure form for more than three inventors)**

**I agree that all rights and royalties will be distributed per Santa Clara University's current patent policy as stated in the Faculty Handbook section 3.7.5. The categories of inventions defined in the Faculty Handbook are also described on page 1 of this disclosure form. I understand that the University will determine the invention category based on any third party agreements and/or the use of funds, materials or facilities administered by the University related to the invention disclosed herein.**

**Inventor's name (print or type): Hohyun Lee**

______________________________________
**Inventor's signature Date**

**Inventor's name (print or type): Madison Gee**

______________________________________
**Inventor's signature Date**

**Inventor's name (print or type): Hector Lopez**

______________________________________
**Inventor's signature Date**

**Inventor's name (print or type): Victor Magana**

______________________________________
**Inventor's signature Date**

7. **Received by (to be completed by Office of Research Initiatives):**

**Form complete:** ☐ **yes** ☐ **no**

**Signature** **Date** **Time**

**If form is incomplete, what information is needed?**

**Date form is completed:**

**Signature** **Date** **Time**

Please submit a hard copy of the completed disclosure to:
Office of Research Initiatives
St. Joseph's Hall
Santa Clara University
500 El Camino Real
Santa Clara, CA 95053

## Appendix G – Senior Design Conference PowerPoint Slides

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### SkyPort: Payload
**Medical Cooler for the SkyPort UAV**


**Madison Gee, Hector Lopez, Victor Magana**
Mechanical Engineering
Santa Clara University Senior Design Conference 2015


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### Motivation for SkyPort

- **Medical logistics**
  - Over 7.5 million children die from malnutrition and mostly preventable diseases annually
  - Poor transportation infrastructure

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### SkyPort Solution

- **Unmanned aerial vehicle (UAV)**
  - Fast and reliable
  - 'Just-in-time' delivery
- **Medical cooler**
  - WHO: Maintain vaccines at 2-8 °C (36-46 °F)
  - Function at ambient temperatures of up to 40 °C (104 °F)
  - Deliver vaccines and return with blood samples

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### Current Products

| Product | Capacity | Cooling Duration | Features |
|---|---|---|---|
| Cool Cube™ 50 | 50 vaccines | 65+ hours | Passive cooling<br>Phase change material |
| ARKTEK™ | ~400 vaccines | 30-60 days | Passive cooling<br>Vacuum chamber |

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### Vaccine Storage

- **High percentage of wasted vaccines**
- **Spoilage due to incorrect storage temperatures**
  - 151 million vaccines lost in developing countries
  - Freezing is more harmful than heating

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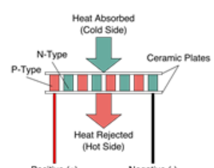
### TEM: Active Cooling

- **Thermoelectric module (TEM)**
  - Peltier effect
  - Temperature difference induced by current
  - Joule Heating




$$Q_C = SIT_C - K(T_H - T_C) - \frac{1}{2}I^2R$$

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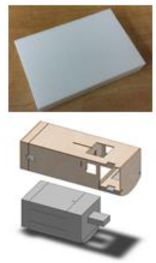
## Outer Insulation

- **Expanded polystyrene foam**
  - High thermal resistance
  - Lightweight
- **Birch plywood shell**
  - Rigid structure



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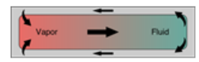
## Heat Dissipation

- **Heat sink and fan**
  - Improve efficiency of TEM
- **Heat pipe**
  - Phase transition
  - High thermal conductivity

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## Inner Chamber

- **6061-T6 aluminum**
  - Machined with a vertical mill
  - Top block holds 6 vials, temperature sensor
  - Bottom block holds 3 blood samples
- **Thermal interface material**
  - Improves conductivity between aluminum faces

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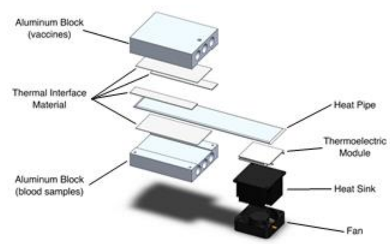
## Heat Removal Components

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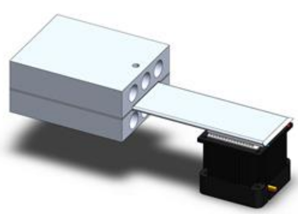
## Heat Removal Components



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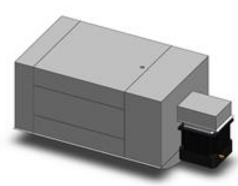
## Outer Insulation



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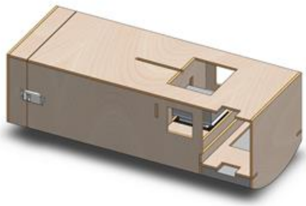
## Outer Insulation



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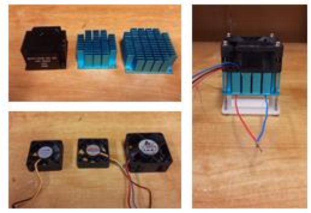
## Integration and Testing

- Fan and heat sink selection



| Black 50 mm Heat Sink | |
|---|---|
| Fan Type | TEM temp. (Celsius) |
| Polar Typhoon | -13.42 |
| Evercool | -14.47 |
| Delta | -12.30 |

| Blue 50 mm Heat Sink | |
|---|---|
| Fan Type | TEM temp. (Celsius) |
| Polar Typhoon | -10.47 |
| Evercool | -4.64 |
| Delta | -4.92 |

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## Integration and Testing

- TEM selection
  - Determine power required to achieve greatest temp. difference
  - Compare TEM performance

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## TEM Optimal Current Tests

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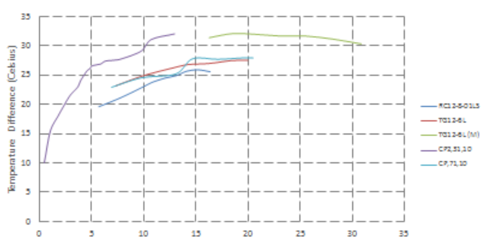
## TEM Optimal Current Tests

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## Temperature Control

- Maintain chamber at 5°C
- Feedforward loop
  - Power Saving Mode
  - Full Power Mode
- Components:
  - Arduino Micro
  - TMP36 temperature sensors
  - Relays
  - Buck converters

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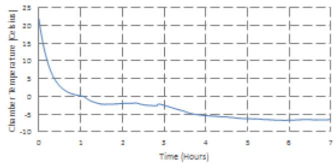
## Feedforward Loop

- **Chamber temperature**
  - Determines operation state (on/off)
- **Ambient temperature**
  - Determines which mode (Power Saving, Full Power)

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## Power Control

- **Buck converter**
  - Step down Power Supply voltage for Arduino and Power Saving Mode
- **Relay**
  - Switch between modes
  - Switch TEM and fan on/off

| Component | Power (mW) |
|---|---|
| Arduino Micro | 500 |
| Buck Converter | 100 |
| Relays (x2) | 200 |
| Total | 800 |

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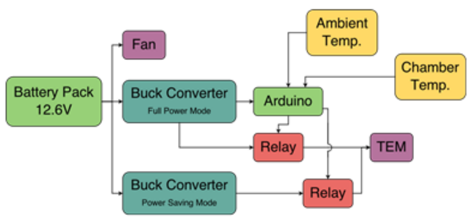
## Temperature Control Schematic

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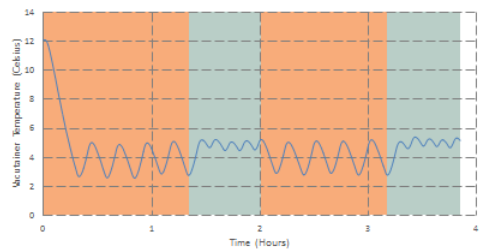
## Temperature Control Test

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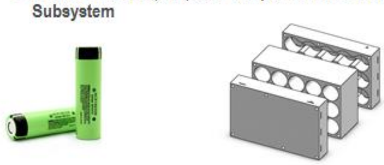
## Power Supply

- **Rechargeable lithium-ion batteries**
  - 15 cells: 3 in series, 5 in parallel
  - Built in protection from over-discharge and over-charge
- **Powers the TEM, fan, and Temperature Control Subsystem**



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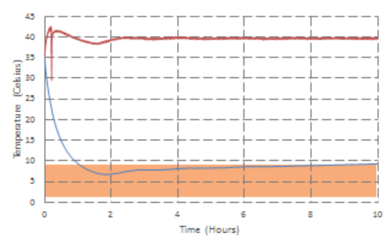
## Battery Life Testing

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## Current Prototype

- 10+ hour operation time
- Maintains temperature at 5 °C (41 °F)
- Consumes 12.9 Watts
- Weighs 2.0 kg (4.4 lb)

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## Cost Analysis

| Subsystem | Cost |
|---|---|
| Insulation/Outer Shell | $4 |
| Heat Removal | $72 |
| Power Supply | $143 |
| Temperature Control | $36 |
| Total | $255 |

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## Future Additions

- Implement more efficient TEM
- Temperature control refining
- Improve user interface
- Optimize design for mass production
- Increase storage capacity

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## Acknowledgements

Willem P. Roelandts and Maria Constantino-Roelandts Grant Program
Santa Clara University School of Engineering
Dr. Hohyun Lee
Donald Maccubbin
Brandon Ohara
Joseph Soares
Zoe Demertzis
Cris Madrigal

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## Appendix A: Cost Analysis

| Components | Volume (in³) | Cost per Volume | Cost |
|---|---|---|---|
| Insulation/Outer Shell | | | |
| EPS Foam | 238.2624 | 0.0023 | $0.54 |
| Birch Plywood | 40.2500 | 0.0769 | $3.10 |
| Heat Removal | | | |
| Aluminum | 17.8324 | 0.7682 | $13.70 |
| Heat Pipe | N/A | N/A | $1.00 |
| Heat Sink | N/A | N/A | $6.54 |
| TEM | N/A | N/A | $40.00 |
| Fan | N/A | N/A | $10.00 |
| Power Supply | | | |
| Battery (x15) | N/A | N/A | $142.13 |
| Temperature Control | | | |
| Relay (x2) | N/A | N/A | $6.00 |
| Buck Converter | N/A | N/A | $9.00 |
| Arduino Micro | N/A | N/A | $21.00 |
| Total | | | $253.00 |

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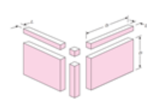
## Appendix B: 3D Shape Factor

| | |
|---|---|
| Conductivity k: (W/mK) | 0.03 |
| Inner Length (mm) | 125.4 |
| Inner Width (mm) | 72 |
| Inner Height (mm) | 42 |
| Wall Thickness (in) | 1 |
| ΔT (°C) | 35 |



| Walls A/L (area/thickness) | | | |
|---|---|---|---|
| Area | Quantity | S | Swall |
| 0.00903 | 2 | 0.71093 | 1.36375 |
| 0.00527 | 2 | 0.41471 | |
| 0.00302 | 2 | 0.23811 | |
| Edges 0.54D (0.54*length) | | | |
| D | Quantity | S | Sedge |
| 0.1254 | 4 | 0.27086 | 0.51710 |
| 0.072 | 4 | 0.15552 | |
| 0.042 | 4 | 0.09072 | |
| Corners 0.15L (0.15*thickness) | | | |
| Scorner | | | |
| 0.03048 | | | |

| | |
|---|---|
| Swall | 1.36375 |
| Sedge | 0.51710 |
| Scorner | 0.03048 |
| Soverall | 1.91133 |
| R | 17.4396 |
| q | 2.00690 |

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